Collapsible Behaviour of Pond ash

Jyotirmayee Mallick

Department of Civil Engineering
National Institute of Technology Rourkela

COLLAPSIBLE BEHAVIOUR OF POND ASH

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree

Of

Master of Technology

In

Civil Engineering

By

JYOTIRMAYEE MALLICK

DEPATMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

2106

COLLAPSIBLE BEHAVIOUR OF POND ASH

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree

Of

Master of Technology

In

Civil Engineering

WITH SPECIALISATION IN

GEOTECHNICAL ENGINEERING

Under the guidance and supervision of

Dr. Chittaranjan Patra

Submitted by:

Jyotirmayee Mallick

(ROLL NO.-214CE1462)

DEPATMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

2016

Civil Engineering
National Institute of Technology Rourkela

Dr. Chittaranjan Patra
Professor

May 26, 2016

Supervisor's Certificate

This is to certify that the work presented in this thesis entitled "*Collapsible behaviour of Pond ash*" by "*Jyotirmayee Mallick*", Roll Number 214CE1462, is a record of original research carried out by her under my supervision and guidance in partial fulfilment of the requirements of the degree of *Master of Technology* in *Civil Engineering*. Neither this thesis nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

Dr. Chittaranjan Patra

Dedicated to my parents

Declaration of Originality

I, *Jyotirmayee Mallick*, Roll Number *214CE1462* hereby declare that this thesis entitled "*Collapsible behaviour of Pond ash*" represents my original work carried out as a postgraduate student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the thesis. Works of other authors cited in this thesis have been duly acknowledged under the section "References". I have also submitted my original research records to the scrutiny committee for evaluation of my Thesis.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present thesis.

May 26, 2016

NIT Rourkela

Jyotirmayee Mallick

Acknowledgment

This thesis is a result of the research that has been done at National Institute of Technology Rourkela. During this period, I came over with an extraordinary number of individuals whose commitments in different ways helped my field of exploration and they merit exceptional much obliged. It is a delight to pass on my appreciation to every one of them. I am profoundly thankful to National institute of Technology, Rourkela for giving me the chance to seek after my Master's degree with all essential facilities. In any case, I might want to express my profound feeling of appreciation and obligation to my supervisor Prof. Chittaranjan Patra for his priceless exhortation, and direction from the developmental phase of this research and giving me phenomenal encounters all through the work. Most importantly, he gave me resolute consolation and support in different ways which enlivened and advanced my circle of learning. It is an amazing privilege to have him as my supervisor. I would also like to thank my committee members, Professor, Shishir Sahoo; Head of the Civil Department. And also I am sincerely thankful to Prof. S. P. Singh, Prof. N. Roy, Prof. S. k. Das, Prof. R.N. Behera, Prof. S. Patra and Prof. R. B. Bag for their kind cooperation and necessary advice. I might want to express my appreciation to all the faculty and staff individuals from the Department of Civil Engineering, National Institute of Technology Rourkela for their consistent backing and good support.

I express to my uncommon on account of my dear companions for their persistent bolster, recommendations and adoration. I am incredibly obliged to my parents for their encouragement and endless support that helped me at each progression of life. Their favours and wishes have empowered me to finish my work effectively.

May 26, 2016 | *Jyotirmayee Mallick*
NIT Rourkela | Roll Number: 214CE1462

Abstract

Vitality necessities for the creating nations like India specifically are met from coal based thermal power plants, where 75% of the aggregate force acquired is from coal-based thermal power plants. The coal used for power generation contains 30–40% of ash. The fly ash generation is more because of high ash coal. The fourth position acquired by the India on the world in the generation of coal ash as waste by-product after USSR, USA and China, in a specific order. Pond ash is the by-product of thermal power plants, which is a waste material and its disposal is a most important problem from an environmental point of view and also it needs a lot of disposal area. Acquiring open lands for disposal in creating nations. For example, India is troublesome, where the area to-population proportion is little. The area and population proportion is less so the area necessity and the expense of the area are expanding step by step, it is key to recover or enhance these ash beds so that the area could be used for the development of light and moderate common foundations. The slack ash fill structures may be susceptible to to collapse on wetting. So a research is carried out to observe the factors affecting the collapse of compacted ash fill on flood. If the ash beds intend to be used as footing subgrades to support civil infrastructure so we need to know its collapsibility behaviour. In the current work, importance has been given on the factors that affecting the collapse settlement of the compacted coal ash due to moistening. For this experimental study is taken up to known the collapsible potential of Pond ash. Attempts have been made to correlate the ash characteristics and the specific placement parameters such as dry unit weight, moisture content, and compaction energy and stress level at wetting with collapse. This was based largely on the single oedometer collapse test results. A sequences of tests, like, direct shear test, light compaction and in addition substantial compaction test are performed to evaluate the quality attributes of compacted pond ash and also tests like specific gravity test, grain size distribution test by mechanical sieve analysis and hydrometer test etc. are performed to get more or less physical properties of the pond ash. Total 145 single oedometer collapse tests were conducted to get the collapse potential of pond ash. The results of oedometer test were very much helpful for evaluating the factors affecting the collapse potential of pond ash.

Key words: Pond ash, collapse potential, compaction test, single oedometer test, moisture content, dry unit weight, vertical stress, compaction energy.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

Now-a-day large amount electrical power utilized by the growing population and developing industries for different applications and necessities. The large amount of power is generated from the thermal power plants which utilize pulverised coal as fuel. About 40-50 % of ash contained coals are generally used in India. Which is higher than the coals utilized in the United States, Germany and Canada. Coal ash is the by-product of thermal power plants, which is as a waste material and its disposal is a major problem from an environmental point of view and requires large disposal area. Acquiring open areas for disposal in developing countries like India is difficult, where the land-to-population ratio is less. Actually, there are three types of ash produced by thermal power plants. They are fly ash, bottom ash and pond ash. The finer fraction of ashes which are collected in the electrostatic precipitators of thermal power plants is knows as fly ash. The heavier and coarser coal ash collected from furnace bottom is known as bottom ash and around20-25% of the total coal ash production. Routinely, these two sorts of ashes are blended completely with water and sluiced to nearby storage ponds called ash ponds. The ash settled in the ash ponds is known as pond ash. The amount of pond ash produced by thermal power plants is very large as compared with other two ashes. The utilization of pond ash to the maximum possible extent is still a major task throughout the world. Indian produce around 90×10^6 ton of coal ash every year which covers an area of 268 km^2 as ash ponds. In a 5 year working period, it is evaluated that a 520 mw thermal power plant can produce coal ash that can be spread over an area of up to 10 km^2 and height of 10 m and that height can be expanded to 30-50 m with time. As the land requirement and the expense of land are increasing day to day, it is most important to recover or enhance these ash ponds so that the area could be utilized for the construction of light and medium civil infrastructures. Pond ash being utilized as a few geotechnical uses like construction of roads and highway embankments, backfilling, land improvement, raising of ash dyke, filling low territories as development fills. Pond ash has potential uses in various ranges.

Coal ash which can be utilized for soil developments has increased remarkable impetus during the last two eras. Primary uses of pond ash are stabilizedvwith lime, as a highway sub grade 1960s (Davidson & Handy 1960; Snyder and Nelson 1962). In 1970s the variation of coal ash applications improved (Copp & Spencer 1970; Joshi et. al 1975), and uses including cement stabilized pond ash were presented. Blended ash can be utilized in land reclamation (Turgon 1988). In recent years the coal ash was considered as a structural fill material without any additives (Indraratana et al. 1991; Sood et al. 1993; Walia et al. 1995; Trivedi et al. 1996).

In any case, the present situation of the use of pond ash in India is terrible. Around 8% of the produced fly ash is being utilized commercially. This demonstrates that there exists a tremendous potential of use of pond ash in geotechnical constructions with a specific end goal to safeguard the important top soil.

Pond ash freshly dumped into a pond

Dry pond ash visible across a huge area

Figure 1.1 Disposal of Pond ash

The coal ash can be utilized as a structural fill material without any additives. It was known that a slack ash fill structure may be prone to collapse on saturating. So an examination was done to observe the reasons that inducing the collapse of compacted ash fill on flood. The general characteristic of collapsible soils are a huge and a sudden volume decrease at a constant stress when flooded with water. When the placement moisture content is dry to optimum at that time the structures like embankments, road fills, structural fill may collapse. The soil that shows collapse have opentype of structure with a high void ratio as expected in the case of ashes. As per Barden et al. (1969) the collapse mechanism is minimised by three factors. The first factor is a potentially unstable structure and the second factor is a high applied pressure and the third factor is a high suction which dissipates on saturating. According to an observational study by Meckechine (1989), the dry density and moisture content are generally considered as critical factors that regulates the collapse of metastable structure of soils, if the dry density is under 16 kNm^{-3}. Jennings and Knight (1975) specified that collapse behaviour is also depend on the clay fraction. An experimental work program was done to study the impact of ash features, dry density, and water content and stress level on the collapse of ashes.

DIFFERENT MODES OF COAL ASH UTILIZATION DURING THE YEAR 2014-15

The coal ash data obtained from Thermal Power Stations for the year 2014-15 has been analysed to find out the modes in which coal ash was utilized and the amount utilized in every mode.

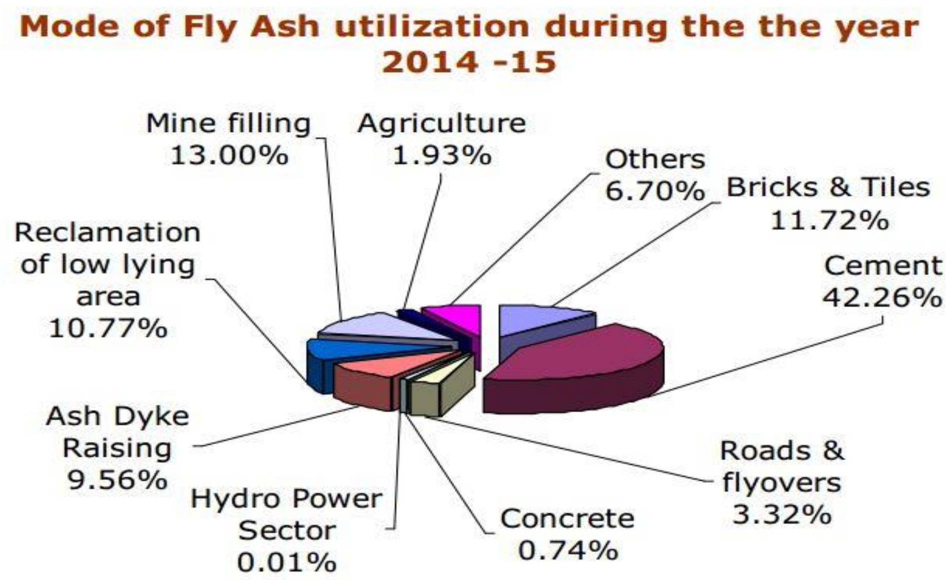

Figure 1.2 Usage of fly ash in recent time.

The mode in which the coal ash were used in the year 2014-15 along with utilization in every mode are presented in Table-1.1.

Table 1.1 Modes of coal ash utilization during the year 2014-15

Sl. No.	**Modes of Utilization**	**Quantity of fly ash utilization in the mode of utilization**	
(1)	**(2)**	**(3) Million-ton (%)**	**(4) Percentage**
1	Cement	43.33	42.26
2	Mine filling	13.33	13.00
3	Bricks and Tiles	12.02	11.72
4	Reclamation of low lying area	11.04	10.77
5	Ash dyke raising	9.80	9.56
6	Roads and Flyovers	3.40	3.32
7	Agricultures	1.97	1.93
8	Concrete	0.76	0.74
9	Hydro power station	0.0054	0.01
10	Others	6.86	6.70
	Total	**102.5433**	**100.0**

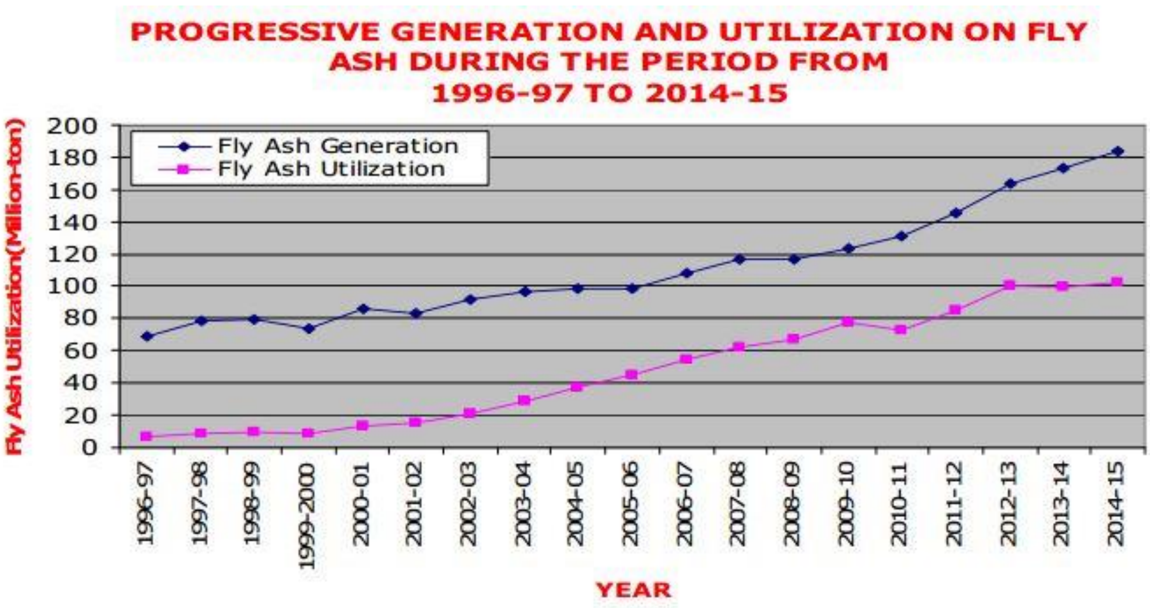

Figure.1.3 Fly ash generation and utilization over the years

It is seen from Figure 1.3 above that:

(i) Since 1996-97 the fly ash generation as well as utilization has generally been increasing.

(ii) Fly ash utilization has been of highest level in the year of 2009-10.

(iii) The fly ash generation has increased nearly 2.5 times in 2014-2015.

(iv) Coal ash use has risen from 6.64 million-ton in 1996-97 to 102.54 million ton in 2014-15 i.e. almost more than 15 times.

In this way, an effort has been made to examine the collapse behaviour of coal ash at various water content, dry densities and stresses in detail. It was found out that the ash having a stamped morphological change with the soils required a different criterion for the ordering of its collapsibility. A new range of collapse potential was assigned for the ashes based on the oedometer collapse test.

2. LITERATURE REVIEW

2.1 POND ASH

The result of combustion of coal is pond ash, it is a mixture of both bottom ash and fly ash and mixed with water to form slurry, then this slurry is supplied to the ash ponds. The ash gets settled in ash pond and the additional water is separated out. Pond ash is the settled ash in ash pond. This can be utilized as filling materials including as a part of construction of embankments and roads. Pond ash can also be used for manufacturer of building products. Pond ash is mainly obtained from the thermal power plants. Copper, aluminium and steel plants also produces pond ash as by-product but in less amount.

Booth (1977) described the collapse settlement in compacted soil in South Africa where collapse settlement occurred in road embankments following wetting of the soil. Oedometer test were conducted over a range of saturation, on soils from four of the embankments. The influence of variation in initial dry density, compaction moisture, applied pressure and particle size distribution is discussed and concluded that (i) collapse can be minimised at initial compacted to a dry density that is greater than 1650 kgm^{-3} (ii) the specimen is compacted at low moisture contents to experiences both greater collapse and greater collapse settlement (iii) the amount of collapse depends to some extent on both soil grading and mineralogy.

Houston et. al (1988) tested a series of oedometer test to predict the collapse of soil. A field test is directed to give a level to compare with expectations and lab test results.

Lawton et. al (1989) conducted compression tests of one-dimensional to explain the impact of compaction water content, compaction method, vertical stress, relative compaction and load wetting sequence on post-compaction wetting made volume change in a moderately plastic clayey sand.

Tadepalli et.al (1990) were conducted tests on compacted soil specimens in two phases. In phase 1 tests were implemented to relate collapse amount to soil properties. Test in phase 2 were done to evaluate the influence of primary matric suction to collapse behaviour. The results concluded that the collapse occurrence is related to the decrease of the matric suction during flood.

Basma et. al (1992) examined the effect of compaction water content, soil type, initial dry unit weight and applied pressure at saturating on collapse potential. They conducted 138 single odeometer tests on 8 dissimilar soils. The result showed that fine graded soils tends to collapse more than the poorly graded one under equal conditions and the collapse potential declines with rise in clay and sand percentages, water content, initial dry density, whereas at wetting it increases with pressure.

Kaniraj et. al (2004) conducted test on fly ash obtained from dadri thermal power station for its geotechnical application. The testing program comprised the classification tests, the consolidation test, the compaction test and the permeability test. The result concluded that the k value were in the same range as in case of non-plastic silts. They equated among the class F fly ash and dadri fly ash has slightly permeable and slightly compressible.

Trivedi et al (2004) investigated to analyse the various factors that inducing collapse settlement of the compacted pond ash due to moistening. They correlated between the ash type, degree of compaction, soluble content, over consolidation ratio, moisture content and stress level at saturating with collapse potential. They recognised the collapsible and non-collapsible ashes by the results of oedometer test and laboratory model test and field collapse test.

Das and Yudhbir (2005) provided the exploratory studies concerning some regular designing properties like grain size, particular gravity and unconfined pressure quality of both low and high calcium fly ash, to assess their reasonableness as bank materials and recovery fills. Also, morphology, science, and mineralogy of fly ash were focused on utilizing examining electron magnifying instrument, electron dispersive x-beam analyser and x-beam diffractometer.

Kim and Salgado (2005) described the test result on 3 mixtures of fly and bottom ash with various mixture ratio and the result indicates that the high proportion of fly ash mixtures are suitable for use in highway embankments.

Jotisankasa et. al (2007) examined the collapse behaviour of unsaturated soil using suction monitored oedometer tests. They used the new technique for investing collapse behaviour.

Sheng et. al (2007) presented the results of a series of triaxial tests on the behaviour of collapse which contains characteristics such as volume changes and saturation changes. The test data demonstrates that the collapse arises primarily in an intermediate range of suction levels, which is neither very low nor very high.

Trivedi (2007) evaluated the settlement characteristic of the coal ash. Experimental study done on coal ash formed at Ropar power station, India for settlement prediction. The settlement was achieved for the rigid plates having less dimension which is more than 0.3 m on ashes. The expected settlement based on the data of coal ash using conventional methods for soils was conservative.

Mansour et. al (2008) conducted single and double oedometer test for calculation of the potential collapse of undisturbed sample of soil. Modified oedometer test was conducted for more exact evaluation of the potential collapse. For cohesive soil single oedometer is not suggested as the deceasing of permeability at the loading (200kPa) but single oedometer test is recommended if the soil is not homogeneous.

Naresh (2010) described to decrease the effect of ash disposal on the environment So it is essential to manage safe environment of ash dyke during construction, while disposing, while raising the dyke. He presented on planning of safe dyke, management of ash disposal for coal based thermal power project.

Arumugam and Manohar (2011) did test study to inspect the likelihood of utilizing pond ash as a part of fluctuating rate as fine aggregate substitute in cement concrete. Pond ash varies from fly ash remains gathered from Electrostatic precipitators in a dry form which contains noteworthy measure of moderately coarser particles. They talked about with the workability and compressive quality of cement and is to be likened with cement. The outcome shows that the density of solid declines with the expansion in rate of pona ash and the compressive quality of cement with pond ash increments with expanded curing period.

Sarkar and Shahu (2012) investigated the geotechnical properties of the coal ashes collected from Dadri, Badarpur and Rajghat power plant located in Delhi and also investigated the properties of pond ash when it mixed with the waste Marble dust which is a by-product during cutting of marbles.

Schanz and Ibrahim (2013) investigated the collapsible potential of different collapsible soil. They determined that, the increase in potential of collapse has direct relationship with overburden effective pressure to join the soils comprising high amount of gypsum and Single

Oedometer Test gave more exact and higher values of (Ic) than the Double Oedometer Test due to more dropping of cementing agent.

Assia and Nabil (2013) did experimental study on a clayey soil used in engineered barriers in Tlemcen which is located in the north west of Algeria. The twelve experimental tests carried out on the saf-saf soil, compacted at different dry densities (1.62, 1.4 and 1.2 gm/cc) and different water contents (20, 18, 15 and 10%). The test of collapse carried out and it shows that for constant water content (constant suction), the potential of collapse rises when the dry density reduces.

Bagwan et. al (2014) investigated the properties of concrete in fresh and harden state. The result reveals that with the rise in the percentage of coal ash the compressive strength of concrete reduces. It is also observed that early age compressive strength of pond ash concrete is low but it is gradually rises as age of concrete increases and it gives good strength.

Gupta et. al (2015) conducted consolidation test on fly ash (FA), bottom ash (BA) and mix of the two (45% FA and 55% BA) to study the various factors which are influencing the collapsible behaviour of coal ash. The results revealed that BA and the mixture of the two ashes shows negligible collapse while the FA is more susceptible to collapse.

.

3.1 THE COLLAPSE MECHANISM

The mechanism of collapsible soil is generally dependent on the soil structure. The collapse phenomenon are explained as below:-

- A fine grained soil present in the large grained particles acts as a bonding material and these bonds experience local compression in the small gaps between adjacent grains resulting in the development of strength. After rising of the overburden pressure due to the construction, these soils compress slightly at natural water content, but the structure remains sensibly unchanged. However, when the loaded soil is exposed to moisture , the fine silt or clay will soften, weaken and/or dissolve to some extent as the critical moisture content is exceeded ;finally the structure collapse.

3.2 Collapsing Soil Structure

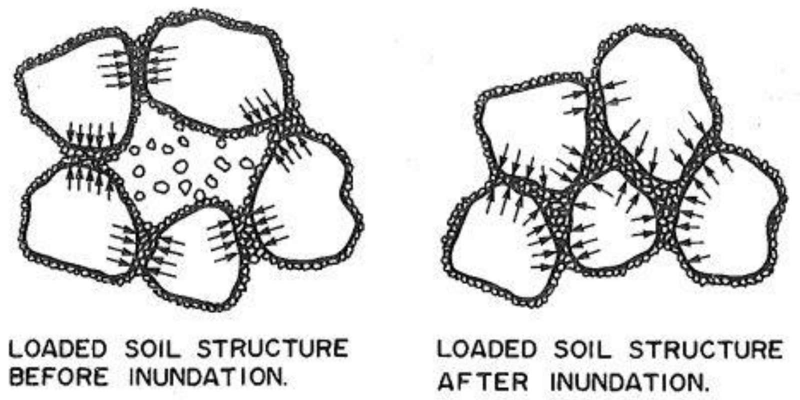

Figure 3.1. Silt/Clay structure suggested by casagrande (1932) Before and After Inundation

The structure comprises of hard unweathered grains, detached by huge open spaces, the shorter separations between nearby particles being possessed by irregular flocculated clay bridges which frequently include within them small unweathered particles. These bridges are in stable equilibrium between the largest intergranular pressure that they have ever experienc es and the highest moisture content ever experienced. The clay particles are concentrated bet ween particle near-contacts by capillary forces during soil dehydration. These similar forces also cause consolidation of the clay between particles. The clay bridges in conjunction with capillary forces and cementing agents, if existing, form a "glue" which holds the soil fabric in its loose state.

3.3 Validation of the Collapse Mechanism

- Knight (1961) used the optical and the electron microscopes to study the change in soil fabrics in South African soils due to collapse of the soil structure. Knight was able to categorise accumulations of clay particles on the surfaces of the movement side of quartz grains after collapse representing that soil grains actually explained to new positions, pushing clay particles in front of them.
- Holtz (1948) recommended that when the moisture content is dry of optimum the earthen structures such as embankments, road fills and structural fills may collapse.
- According to ASTM (2003), the quantitative amount of collapse settlement is the coll -apse potential (CP) which is the vertical strain of the soil specimen under a definite constant vertical overburden stress due to inundation. The collapse potential at 200 kPa vertical stress is called collapse index (Ic), which can be used to categorise collapsible soils.
- Since research laboratory testing is costly and a time consuming process, several researchers have publicised empirical equations to determine the collapse potential (CP).
    - Basma and Tuncer (1992) tested on eight different soils from Jordan and presented two different equations to evaluate collapse potential:

$$CP = 48.496 + 0.102\ Cu\ 0.457\ wi - 3.533\ \Upsilon_d + 2.80 \ln (Pw) \quad \ldots\ldots\ldots\ldots\ldots.. \quad (1)$$

$$CP = 47.506 + 0.072(S - C) - 0.439\ wi - 3.123\ \Upsilon_d + 2.851 \ln (Pw) \quad \ldots\ldots\ldots\ldots \ (2)$$

Where,

CP = collapse potential (%)

Cu = coefficient of uniformity

wi = initial moisture content

Υ_d = initial dry unit weight

Pw = pressure at wetting

(S – C) = difference between sand and clay content (%)

- Habibugahi and Taherian (2004) initiate the above equations gave poor performance in calculating collapse potential, particularly over small collapse potentials. This might be due to the fact that the use of incorrect parameters like metric suction, which may have important role in conserving the meta-stable loose structure of collapsible unsaturated soil.
- As per Barden et al. (1969) the three factors are generally used to measure the collapse machanism:

1) A potentially unstable structure, such as flocculent type associated with soils compacted dry of optimum or with loess soils

2) A high applied pressure which further increases the instability

3) A high suction which offers the structure with only temporary strength which dissipates on wetting.

- The dry density and water content of soil samples at the time of compaction are generally considered as the primary soil properties that control the quantity of collapse. As per an empirical study by Meckechnie (1989), the dry unit weight and water content are generally considered as essential parameters that control the collapse of metastable structure of soils, if the dry unit weight is less than 16 kN m^{-3}.
- Jennings and Knight (1975) specified that collapse behaviour depends on the clay fraction. Foss (1973) and Reznik (1993) calculate the amount of collapse by

$$CP = dh / h_0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Where

CP = collapse potential

dh = decrease in the height of sample subsequent to inundation

h_0 = height of sample before saturation.

- As per Booth (1975) when the initial dry unit weight is less than 15.7 kN m^{-3} and 85 % the collapse settlement is more than 1 % which is acquired in the modified compaction test.

- The collapse potential is measureable in terms of the volume change that occurs when a soil is submerged with water. The collapse potential is determined by conducting oedometer collapse tests on soil sample. The collapse potential is the ratio of change in void ratio on wetting to the void ratio at the beginning of saturation at any stress level.

$$CP = \Delta e / (1+ei) \qquad \text{……………………..} \quad (4)$$

Where,

Δe = change in void ratio upon wetting

ei = void ratio at the beginning of saturation.

Identification of critical parameters

Take a sample of an undisturbed soil at its natural moisture content → Apply stepped loads up to a pressure of 200kN/m^2 → Flood the sample to saturation and leave for 24 hours.

- Knight (1963) found the collapse potential at a stress level of 200 kPa selecting ei as void ratio at the beginning of compression. If the collapse potential is less than 0.01, then there is no danger of a collapse in the field. Lutenegger and Saber (1988) recommended the use of ei as void ratio before saturation at an applied stress level of 300 kPa. They suggested that if the soil collapse potential value is less than 0.02 then the soil is collapsible. Their researches reveal that the soils which have placement void ratio lies between 0.9 and 1.05 are slightly or moderately collapsible.
- Qian and Lin (1988) informed that naturally occurring collapsing soils can be separated into two types. There are those which collapse upon inundation under a total pressure equal to their overburden, and there are those which require a total pressure greater than their overburden to show the collapse phenomenon.
- Burland (1965) explained the collapse mechanism in relation to the stability at the interparticle contact points. Due to inundation, the negative pore-water pressure at the

contact points reduces, giving rise to grain slippage and distortion. This results in an irrecoverable reduction in total volume.

- Jennings and Knight (1975) had interrelated collapse potential with degreev of severity to the structure. Such as if

Collapse potential	Problem
	No problem
1-5	Moderate trouble
5-10	Sever trouble
10-20	Very danger

- For calculation of collapse of soils, following methods are used:
  - i) Single Oedometer collapse test
  - ii) Double oedometer collapse test
  - iii) Down hole test
  - iv) Double triaxial collapse test
  - v) Laboratory infiltration test
  - vi) Field infiltration test
  - vii) Triaxial A-value correlation with collapse potentials.
- The single oedometer and double oedometer test are generally commonly used for collapse test.

Single oedometer collapse test: The undisturbed soil sample at natural moisture content loaded in the conventional oedometer to a stress level ranging between 200 and 400 kPa and then flood by distilled water is applied to induce collapse. Abelev (1948) used stress level of 300 kPa and defined the collapse potential (Ie) as:

$$Ie = \Delta e_c / 1 + e_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where:

Δe_c : change in void ratio resulting from saturation

e_1 : void ratio just before inundation

While, Jennings and Knight (1975), suggested the using of stress level of 200 kPa and compute the collapse potential according to following equation:

$$Ie = \Delta e_c / 1 + e_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where:

Δe_c : change in void ratio resulting from saturation

e_0 : Natural void ratio

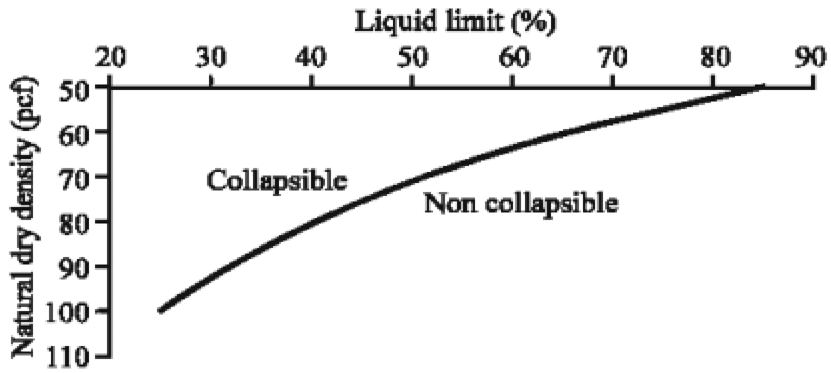

Figure 3.2 commonly used condition for determining collapsibility (Lutenegger and Saber, 1988)

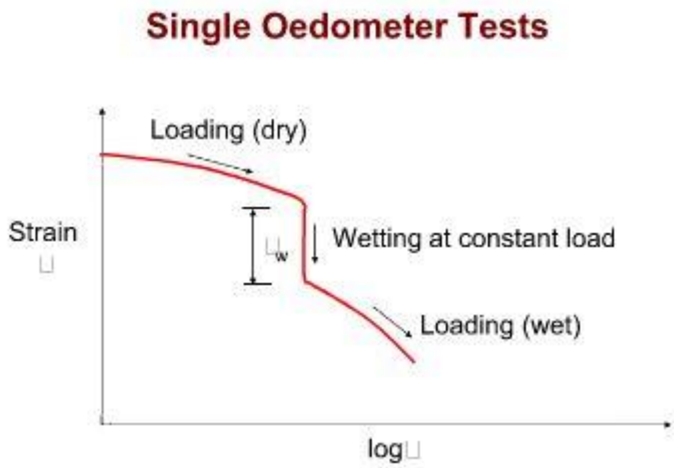

Figure 3.3 Typical Single Oedometer Collapse test Result

Double Oedometer Collapse Test: Two equal samples are placed in oedometers; one tested at in-situ natural moisture content and the other is fully saturated before the test starts and then subjected to same loading. Two stress versus strain curved are produced. The difference between the compression curve is the amount of deformation that would occur at any stress level at which the soil gets inundated. Results from the Double oedometer test are presented in Figure 3.4.

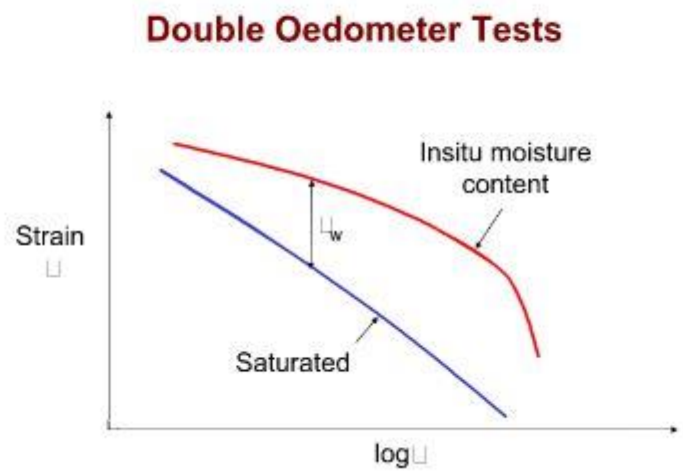

Figure 3.4 Typical Double Oedometer Collapse test Result

In the double oedometer the collapse potential was estimated by using Eq. (6) selecting e_o as void ratio of the dry sample and Δe_c as difference of the dry and submerged sample at a desired stress level.

4. EXPERIMENTAL WORK

4.1 INTRODUCTION

The thermal power plants produces very large amount of ashes. Which nearly occupied 70,000 acres of land by ash ponds. In the present study a test work was led to find out the collapse potential of pond ash. The index as well as engineering properties have been calculated. Details of material used, processing test method accepted are described in this part of the chapter.

The tests which were executed:-

1) Density bottle test to find out specific gravity.

2) Mechanical sieve analysis and hydro meter tests to find grain size distribution.

3) Proctor compaction tests for different water content

4) Liquid limit, Plastic limit and shrinkage limit

5) Swelling index test

6) Permeability test

7) Direct Shear teat

8) Single oedometer collapse test

4.2 MATERIAL USED

1. Pond ash

4.2.1 Pond ash

The current samples are collected from ash ponds of NSPCL Rourkela. The specimens were oven dried at the temperature of 105-110 degrees. Then it was sieved by utilizing required sieves .The material passing through the sieve was utilized as a part of experimental work.

4.2.1.1 Physical parametersof Pond ash

Physical parameter of pond ash is shown in Table 4.1

Parameter	**Value**
Colour	Light grey
Shape	Sub-rounded
Uniformity coefficient	3.67
Coefficient of curvature	1.63
Plasticity index	Non-plastic

4.2.1.2 Chemical Compositions

Chemical composition of pond ash is shown in Table 4.2

Parameters	Value in percentage
SiO_2	59-61
Al_2O_3	28-28.8
Fe_2O_3	2.70-5.52
Na_2O	0.24-0.50
K_2O	1.26-1.76
CaO	0.7-1
MgO	1.40-1.90
LOI	0.5-2.5

4.3 DETERMINATION OF INDEX PROPERTIES

4.3.1 Specific Gravity

The specific gravity of pond ash was calculated as per IS: 2720 (Part 3 section 1) 1980 and shown in Table 4.3.

Table 4.3. Specific gravity of Pond ash

Sl.no.	Wt. of flask(w1)	Wt. of flask+ sample(w2)	Wt. of flask+ sample+ water(w3)	Wt. of water(w4)	Specific Gravity(G)
1	109.53	159.53	385.14	358.87	2.09
2	111.00	161.00	385.97	359.90	2.08
3	112.18	162.18	387.16	361.06	2.09

4.3.2 Determination of Grain Size Distribution

Pond ash comprises both coarse and fine grained particles. For determination of grain size distribution, the pond ash was passed through an IS test sieve having an opening size 75µ. Sieve analysis was performed for coarser particles as per IS: 2720 part (4), 1975 and hydrometer analysis was performed for finer particles as per IS: 2720 part (4). Particle size distributioncurve was plotted between percentages finer vs. particle size. Coefficient of uniformity and coefficientof curvaturewere calculated by using the following formula.

Coefficient of uniformity, $C_u = D_{60} / D_{10}$

Coefficient of Curvature, $C_c = (D_{30})^2 / D_{60} \times D_{10}$

4.3.3 Atterberg limit test

The test for Atterberg limits were conducted as per Indian standards IS: 2720 (part 5) 1985. Both plastic and liquid limits of the ash samples were conducted. Tests conducted to determine the liquid limit from Casagrande's method and Plastic limit by making threads of 3mm in diameter.

4.3.4 Compaction characteristics

Light (standard proctor) compaction tests were conducted to determine the maximum dry density (MDD) and optimum moisture content (OMC) of given pond ash sample as per IS: 2720 (part 7)1980. Compaction tests are generally used to define optimum moisture content-maximum dry density relationship of soil. The test consists in compacting pond ash at various water content in the mould, in three layers, each layer being given 25 blows of 2.6 kg rammer droppedvfrom a height of 31 cm. In case of heavy compaction test pond ash at different water content was compacted in the mould in five layers with 25 blows in each layer given by a rammer of 4.5 kg with a fall of 45 cm. A graph was plotted between moisture content and dry density. From which OMC and MDD values were found out. Compaction tests were conducted for different compaction energy by increasing or decreasing number of blows given by rammer an dshown in Table 4.6.

Table.4.4 Standard Proctor compaction test Result

Properties	Value
Standard proctor test	
MDD(kN/m^3)	10.5
OMC (%)	37

Compaction Proctor results

Table 4.5 Compaction Proctor results

Water content in %	Dry density in gm/cc
31.02	0.93
33.58	0.95
35.42	0.98
36.82	1.05
40.66	1.03
42.95	1.02

Table 4.6 OMC and MDD at different compaction energy

Serial no.	Compaction Energy E(Kg-m/m^3)	OMC (%)	MDD (gm/cm^3)
1	99734.32	38.49	1.056
2	119681.18	36.03	1.070
3	347127.17	33.92	1.115
4	433908.96	30.51	1.165
5	520690.76	30.23	1.174

4.3.5 Free swell index:

Free Swell Index is the increase in volume of a soil, without any external constraints, on submergence in water. Free swell index was conducted as per IS: 2720 (Part 40) 1977.The free swell index is calculated by the formula,

$$\text{Free swell index} = (V_d - V_k) / V_d \times 100$$

4.3.6 Permeability Test:

The coefficient of permeability (k) values calculated from falling head permeameter for pond ash samples as per IS: 2720 (Part 17) 1986. In the falling head permeability test, the coefficient of permeability, k, is calculated by using the formula,

$$k = \frac{aL}{At} ln \frac{hi}{ht} \quad \text{................ (7)}$$

Where,

A = inside area of the burette

A = area of the specimen

L = length of mould

t = elapsed time between the two head loss observations

hi = initial head loss across the specimen at the beginning of the observation

ht = head loss at t.

Since the burette readings were noted at each 10 min interval over a time of 30 min, there were a number of combinations of t, hi , and ht , in which the data could be utilized to estimate the value of k by Eq. (5). The average of these values, k_{av}, was determined.

4.3.7 Direct Shear Test:

Tests were conducted in a 60 mm square and 50 mm profound **shearenclose** which is isolated to two sections on a level plane , with proper separating screws at ordinary stresses of 50 to 150 kPa and sheared at a rate of 1.25 mm/minute as indicated by IS:2720 (Part 13). The subsequent peak friction angle and cohesion value were found at optimum moisture content and maximum dry density.

Table 4.7 Shear parameter at OMC and MDD

Dry density (gm/cc)	Water content (%)	c (kPa)	ϕ (^{0})
1.05	37	5.8	35.22

4.3.8 Single oedometer collapse test:

Single oedometer collapse test was directed according to ASTM D5333-03. The ash was oven dried at 105^0 C for 24 hr. The prepared samples were compacted in to a standard 75 mm diameter and 25 mm thick oedometer ring under a static burden using a uniquely outlined mould. The static procedure was kept the consistency in the specimen however it was perceived that adjustment in the method of compaction additionally impacts the collapse. By figuring accurate measure of ash fundamental for filling the mould, the standard delegate state of dry density and water content separately 1.05 gm/cc and 37% was taken. An example of known introductory dry density was appended in the oedometer ring. The vertical burden was progressively expanded to a desired stress level. The sample was permitted to achieve a harmony distortion at each stress level so that the measure of deformation was under 0.05 mm/h. The specimen was overflowed by the water from the base at a desired stress level through an air dried permeable stones to allow for the getaway of air pockets. The harmony distortion of test was noted on immersion. No less than three test were directed to acquire the mean estimation of the collapse potential, thus a sum of 145 single oedometer test were done to decide the impact of different parameters. These tests were performed on pond ash remains under variable dry unit weight, water content and pressure on wetting.

TESTING METHODS

In order to characterize the collapse potential of Pond ash. We used the method of the simple oedometer test. The procedure used is that recommended by the standard ASTM D5333-1992 (Standard Test Method for Measurement of Collapse potential of Soils) which is a standard for the study of the collapsible soils. The test method involves the placing of a compacted soil specimen at the desired water content in an oedometer, applying a predetermined vertical stress to the sample and inundating the sample with distilled water to induce the potential collapse in the soil specimen.

The test method follows these steps (from ASTM D5333-1992):

1. Place the specimen in the loading device immediately after compaction at the initial conditions of water content and dry density.
2. Enclose the specimen ring with a loose fitting plastic membrane to avoid change in specimen water content due to evaporation.
3. Then apply a seating stress of 5 kPa.
4. Within 5 min of applying the seating stress, apply load increments each hour at initial water content until the appropriate vertical stress is applied to the soil.
5. Load increments should be 12, 25, 50, 100, and 200 kPa.
6. Record the deformation before each load increment is applied.
7. Inundate the specimen with water 1 h after loading to 200 kPa.
8. Record deformation 24 h after the inundation and then continue the load as a classical saturated oedometer test.
9. collapse potential (Ic), percent—relative magnitude of soil collapse determined at any stress level as follows:

$$Ic = \frac{df - di}{h0} x100 \qquad \text{.............................. (8)}$$

Where, *ho* = initial specimen height, (mm)

df = dial reading at the suitable stress level after wetting, (mm)

di = dial reading at the suitable stress level before wetting, (mm)

5.1. INDEX PROPERTIES:

5.1.1 Specific gravity

Specific gravity of pond ash was found to be 2.09.

5.1.2 Liquid limit

Liquid limit is the base water content at which soil is in fluid state yet holds little shear quality against streaming. As the pond ash is non plastic, as far as possible can't be resolved.

5.1.3 Plastic limit

Plastic limit is the base water content at which soil start to disintegrate when it is rolled into a 3mm dia. string. Because of non-plastic nature of pond ash, plastic limit can't be resolved.

5.1.4 Grain size distribution

Grain size distribution curve was determined by sieving and hydrometer analysis. Grain size distribution curve is characterised in Figure 5.1. The coefficient of uniformity and coefficient of curvature were found to be 3.67 and 1.63 respectively.

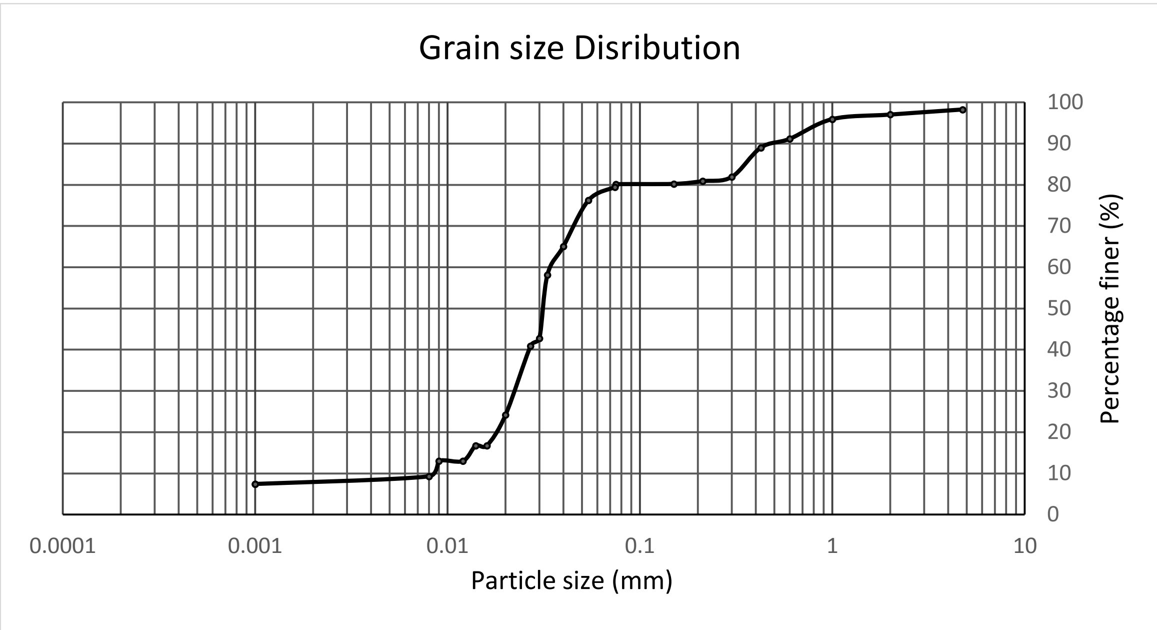

Figure 5.1Grain-size distribution curve of Pond ash

5.2 ENGINEERING PROPERTIES:

5.2.1 Compaction test

Light (standard proctor) compaction tests were carried out to determine the maximum dry density (MDD) and optimum moisture content (OMC) of given pond ash sample that is 1.05 gm/cm^3 and 37 %. Also Compaction tests were carried out at different compaction energy (99734.32 kg-m/m^3, 119681.18 kg-m/m^3, 347127.17 kg-m/m^3, 433908.96 kg-m/m^3 and 520690.76 kg-m/m^3) and equivalent MDD and OMC were found out. Maximum dry density of pond ash is increasing with increase in compaction energy whereas optimum moisture content is diminishing with increase in compaction energy. Figure 5.2 and 5.3 demonstrates the diagram identified with compaction test.

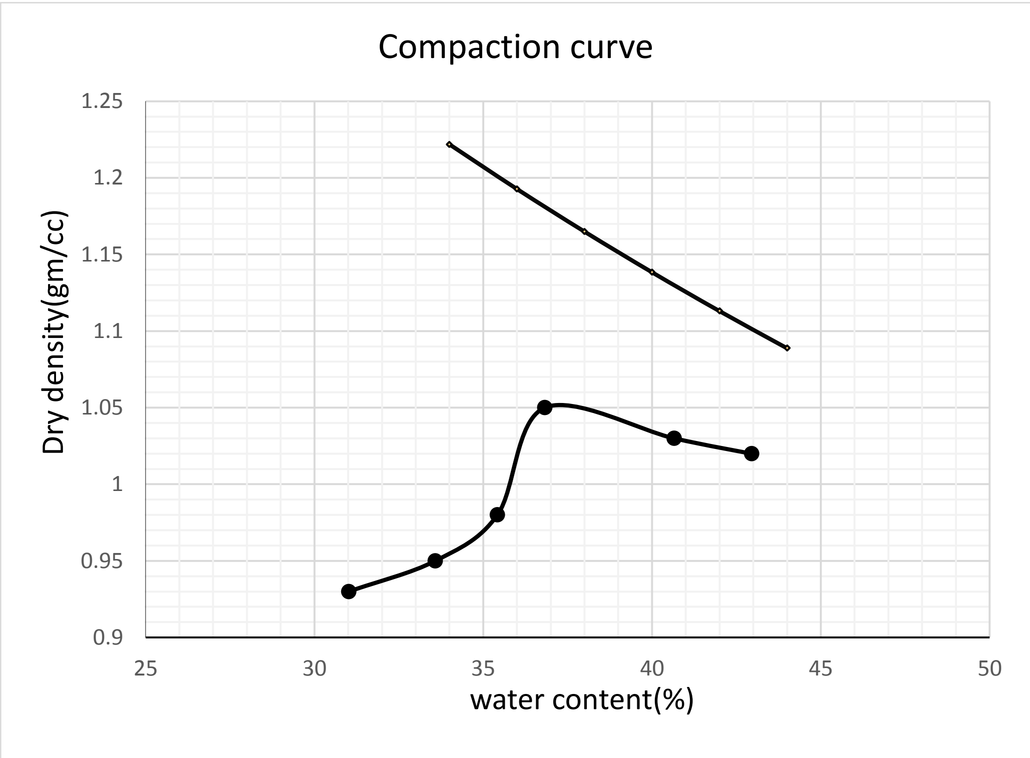

Figure 5.2 Compaction curve of Pond ash

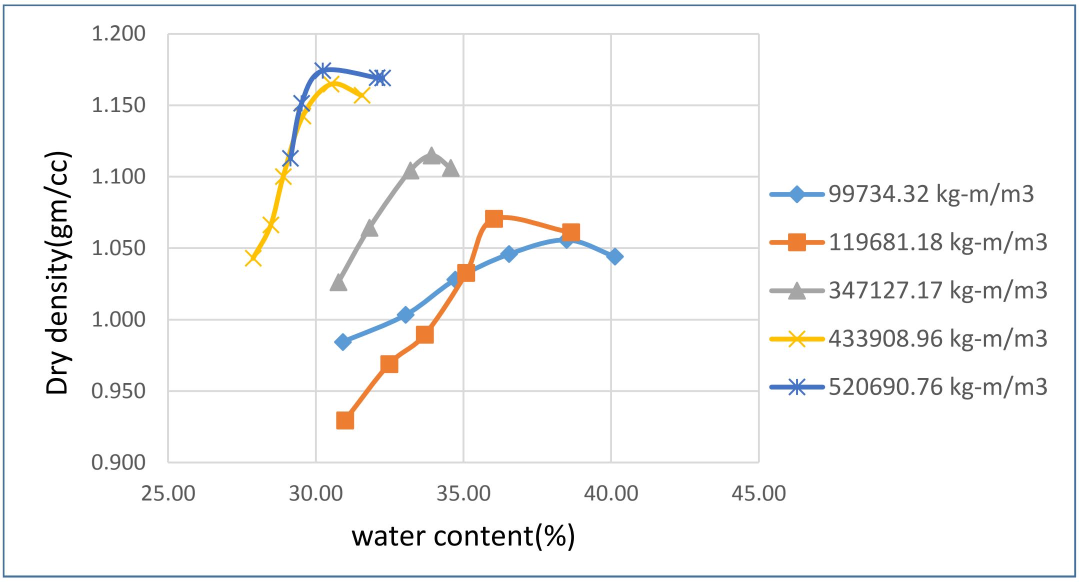

Figure 5.3 Variation of dry density with moisture content at compaction energy

5.2.2 Direct Shear Test

Direct shear test was directed for pond ash at OMC and MDD corresponding to light compaction test. Shear parameters was calculated from the graphvbetween normal stresses vs. shear stress. Results are shown in Table 4.7. Figure 5.4 shows the graph related to direct shear test. When the soil was compacted at light compaction density and moisture content, the unit cohesion and angle of friction are 5.8 kPa and 35.22^0.

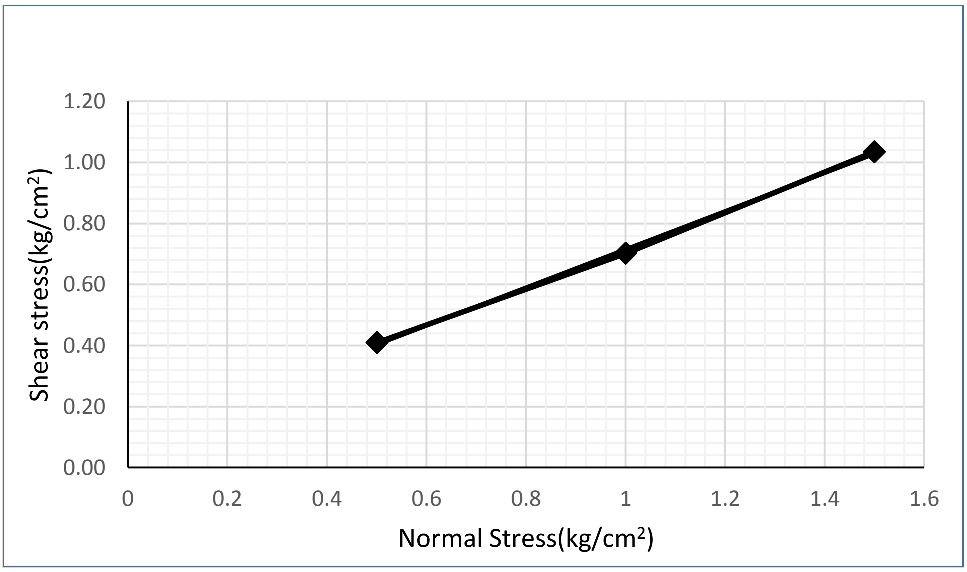

Figure 5.4 Direct shear test result

5.2.3 Free swell index

The free swell index of the given pond ash sample was

$$\text{Free swell index} = (V_d - V_k) / V_d \times 100$$

$$= (60 - 42) / 42 \times 100 = 42.86\ \%$$

5.2.4 Permeability test

Permeability test was conducted to estimate the coefficient of permeability (k).The falling head method is used for fine-grained pond ash samples. The coefficient of permeability is defined as the average velocity of flow that will occur through the total cross-sectional area of the sample. The coefficient of permeability was 5.16×10^{-4} cm/sec.

5.2.5 Single oedometer collapse test

The collapsibility of coal ash is one of the most important parameters for using ash as a fill material. The 145 experimental tests carried out on pond ash, compacted at different dry densities (1.05, 0.84 and 0.63 gm/cm^3) and different water contents (37, 30, 22, 15 and 7%) and different stress level (100, 200 and 300 kPa) gave the results reported in the graphs of Figures 5.5 to 5.41.

5.2.5.1 Collapse Test Result at different Dry Density and at different Moisture Content at a Stress level of 100kPa

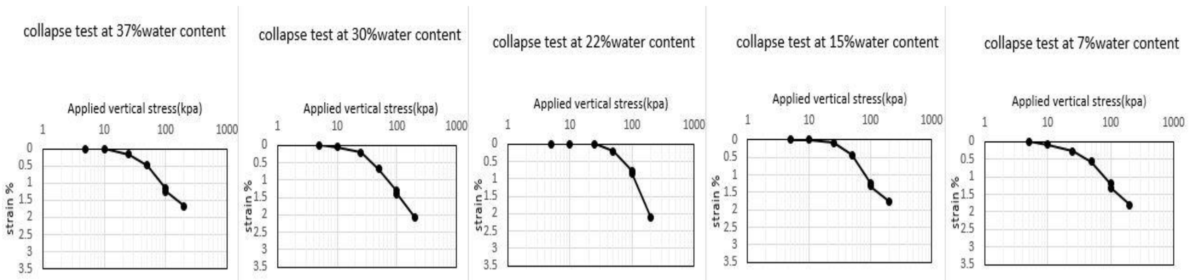

Figure: 5.5 Collapse test Result at dry density of 1.05 gm/cm^3

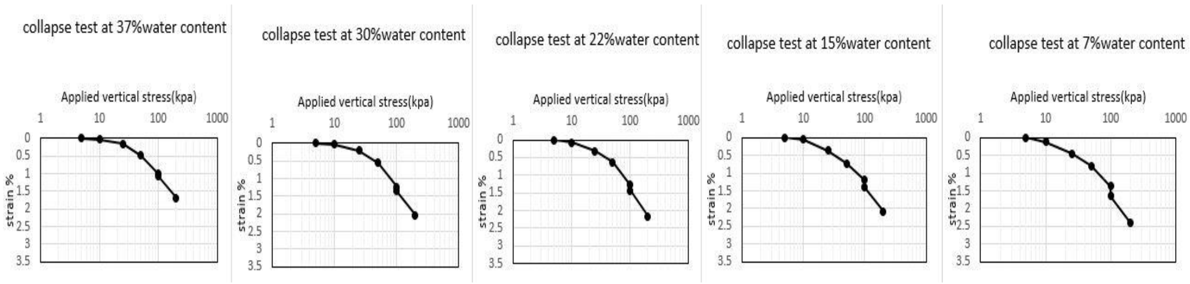

Figure.5.6 Collapse test Result at dry density of 0.84 gm/cm^3

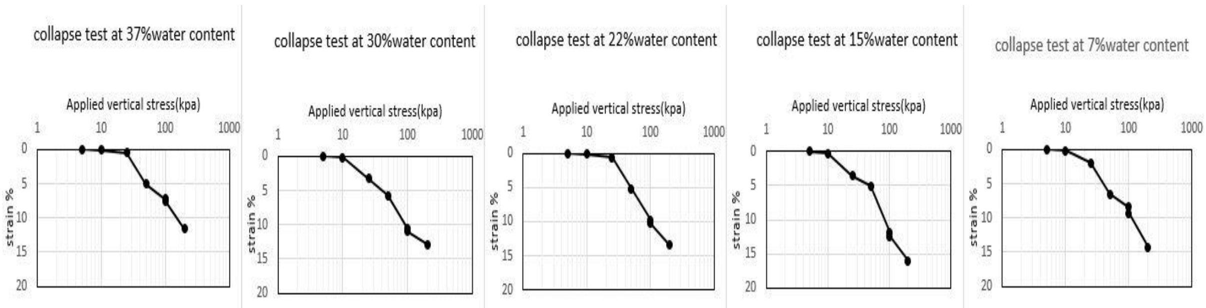

Figure.5.7 Collapse test Result at dry density of 0.63 gm/cm^3

Figure 5.5 to Figure 5.7 shows the test result between applied vertical stress (kPa) vs strain (%). At dry density 1.05 gm/cc and water content 37 % the collapse potential is 0.08% which is less than 1%. It is found that at 100 kPa the collapse potentials are less than 1% at different water content and dry density.

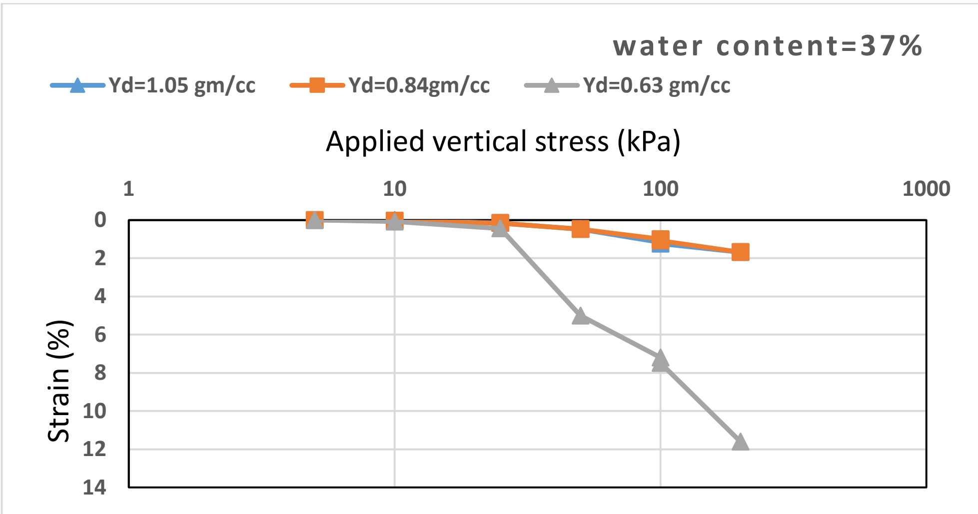

Figure. 5.8 Collapse test Result at different dry density of water content 37%

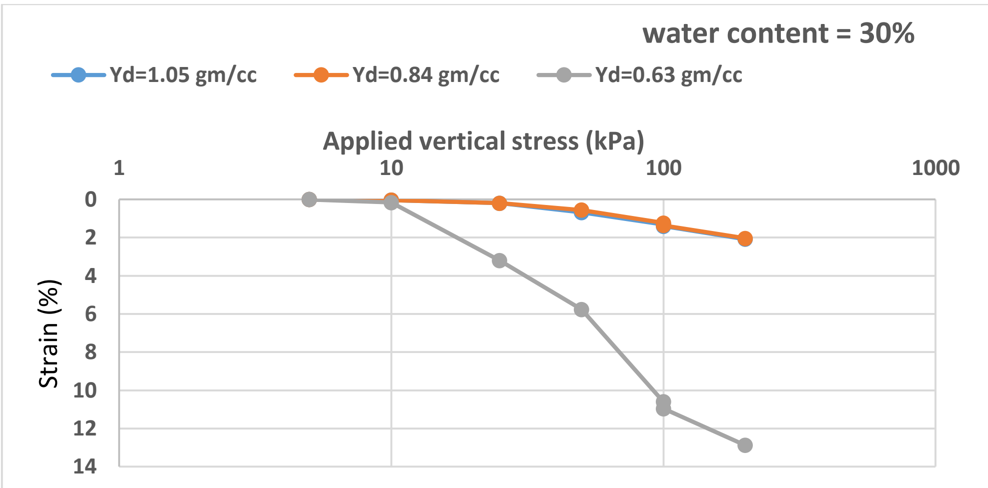

Figure.5.9 Collapse test Result at different dry density of water content 30%

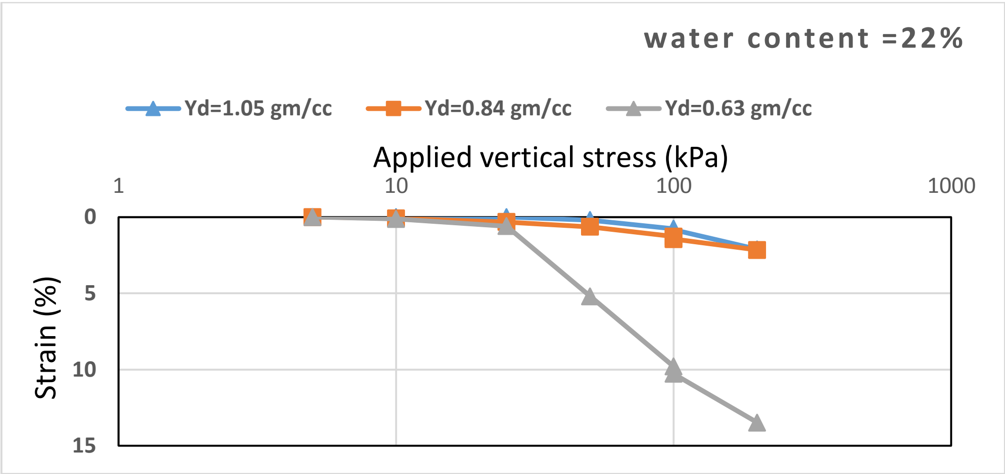

Figure.5.10 Collapse test Result at different dry density of water content 22%

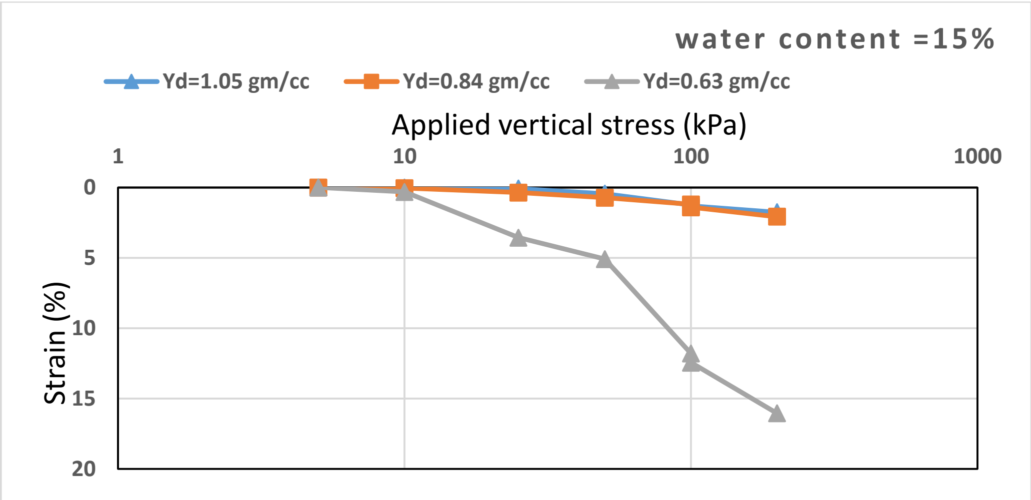

Figure.5.11 Collapse test Result at different dry density of water content 15%

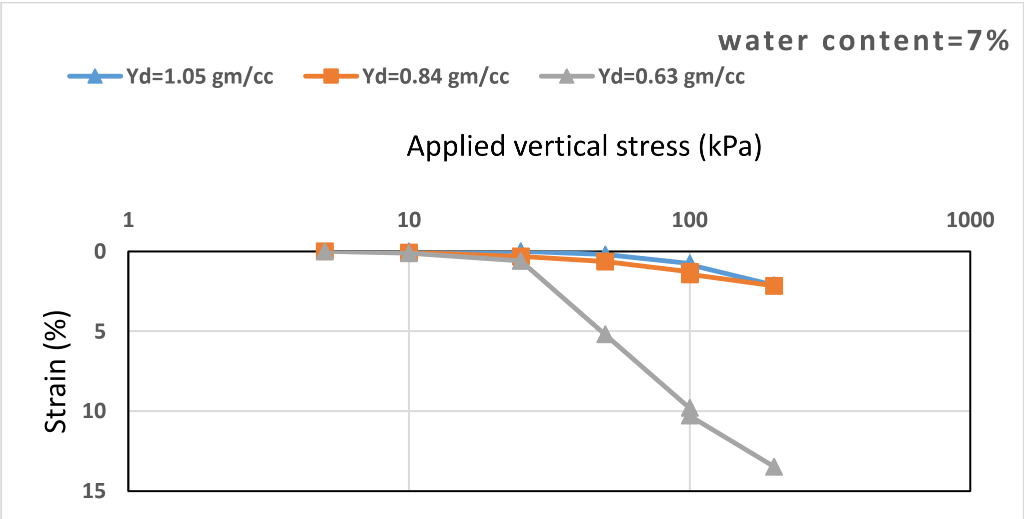

Figure.5.12 Collapse test Result at different dry density of water content 7%

Figures 5.8 to 5.12 the initial water content is respectively 37 %, 30 %, 22%, 15% and 7%. In this case the potential collapse decreases while increasing applied dry density. The highest rate of collapse is obtained for a density of 0.63 gm/cc and a water content of 7%, the rate of collapse is 0.88%. This is phenomenon done by the mechanism that occurs after inundate at load of 100 kPa. In order to establish the influence of dry density and water content on collapse potential of the studied pond ash, shown in Table 5.1 and plotted the variation of collapse potential with both dry density (Figure 5.13) and the water content (Figure 5.14).

Analysing the Table 5.1, the results are:

1. The lowest potential is obtained at the characteristics of standard Proctor optimum (w=37%,Υ_d=1.05 gm/cc)
2. At lower density and water content, the potential of collapse is 0.88% for the studied Pond ash sample which is more than the collapse potential at 37 % and 1.05 gm/cc.

Table 5.1 Potential Collapse of Pond ash at 100 kPa

gm/cc ↓	W=37%	W=30%	W=22%	W=15%	W=7%
Υ_d=1.05	0.08	0.08	0.08	0.08	0.12
Υ_d=0.84	0.08	0.12	0.16	0.20	0.28
Υ_d=0.63	0.28	0.30	0.48	0.64	0.88

Classification of Jennings and Knight (1975)
Legend:

	No Problem (CP from 0 to 1%)		Moderate Trouble (CP from 1 to 5%)
	Trouble (CP from 5 to 10%)		Severe Trouble (CP from 10 to 20%)
	Very Severe Trouble (CP > to 20%)		

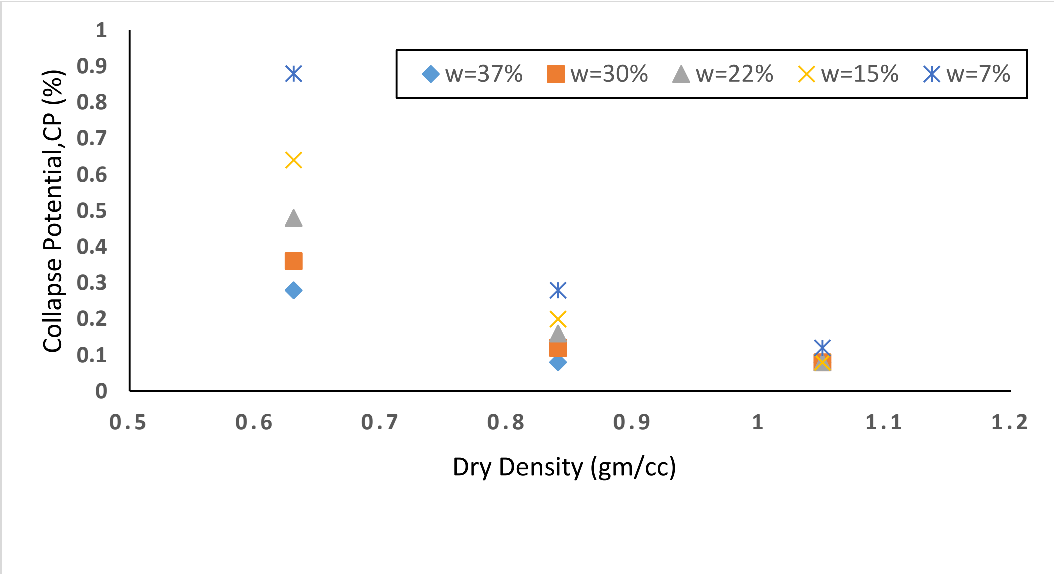

Figure.5.13 Effect of Collapse Potential at different Dry density

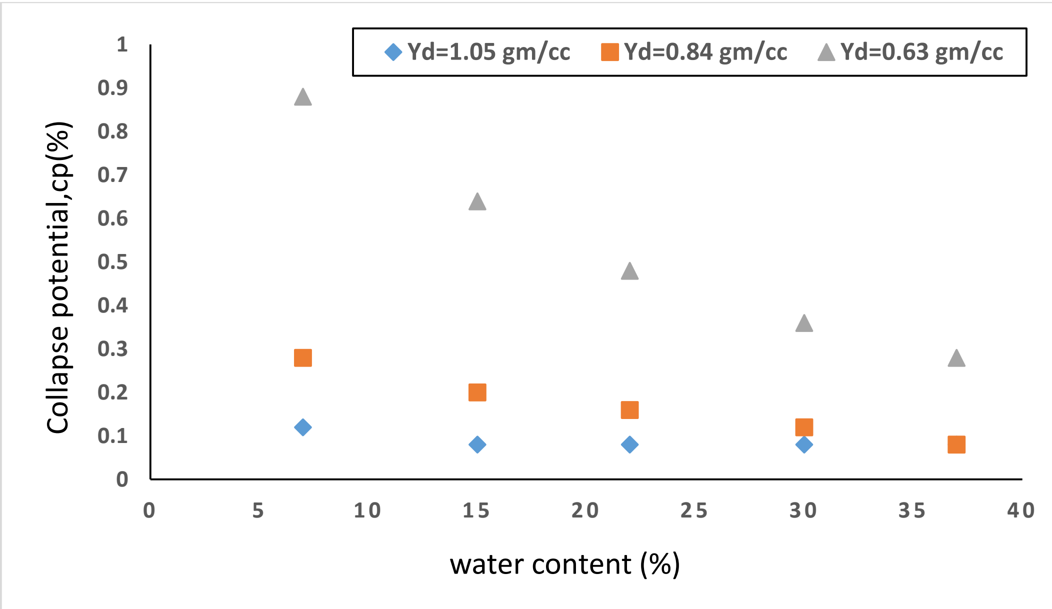

Figure.5.14 Effect of Collapse Potential at different Moisture content

The results in Table 5.1 are expressed as graphs (Figures 5.13 and 5.14). It clearly shows that there is an inverse relation between the collapse potential (CP) and dry density. The same thing is observed for the relation between CP and water content. At higher value of water content, a lowest potential of collapse is obtained. A summary of the potential collapse of the Pond ash in 3D presentation is given in Figure 5.15.

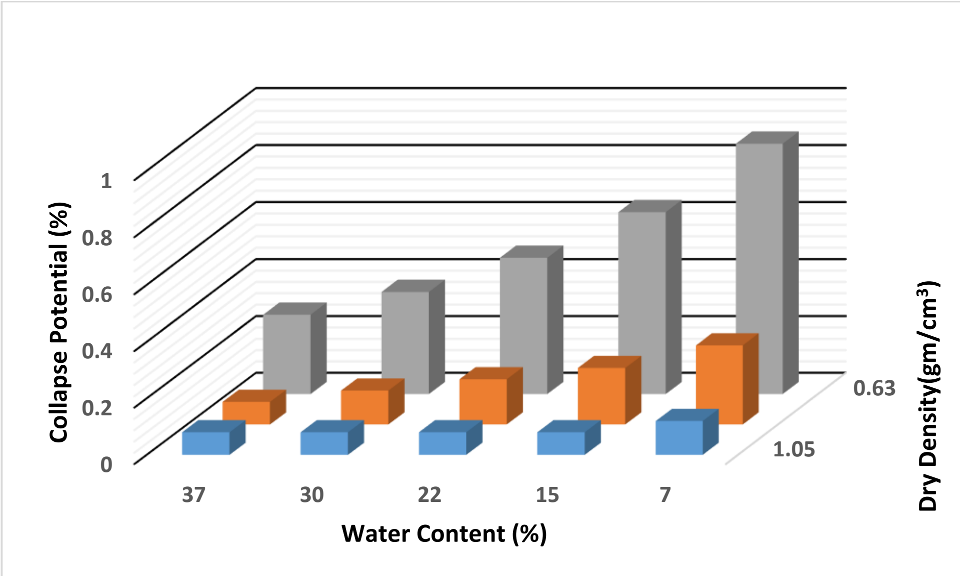

Figure.5.15 Summary of the potential collapse of Pond ash (3D representation).

5.2.5.2 Collapse Test Result at different Dry Density and at different Moisture Content at a Stress level of 200kPa

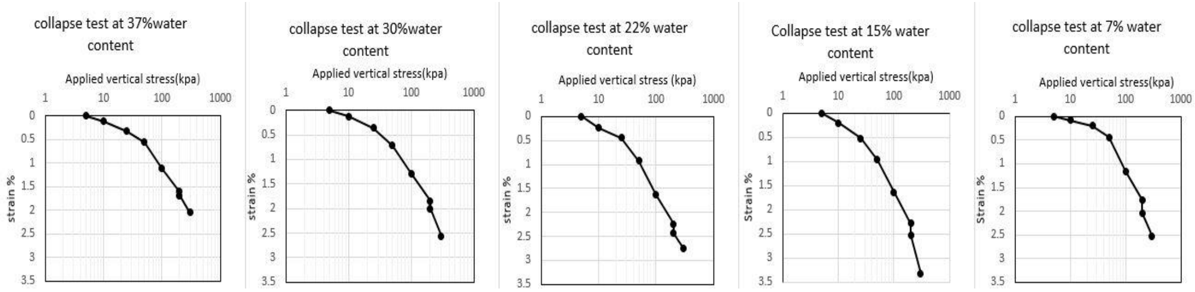

Figure.5.16 Collapse test Result at dry density of 1.05 gm/cm^3

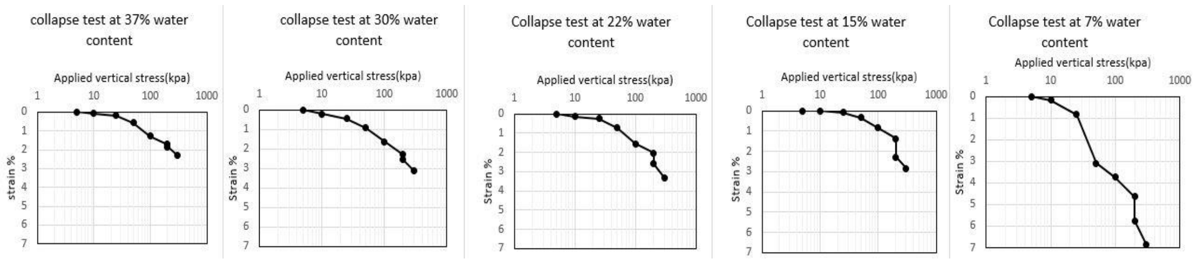

Figure.5.17 Collapse test Result at dry density of 0.84 gm/cm^3

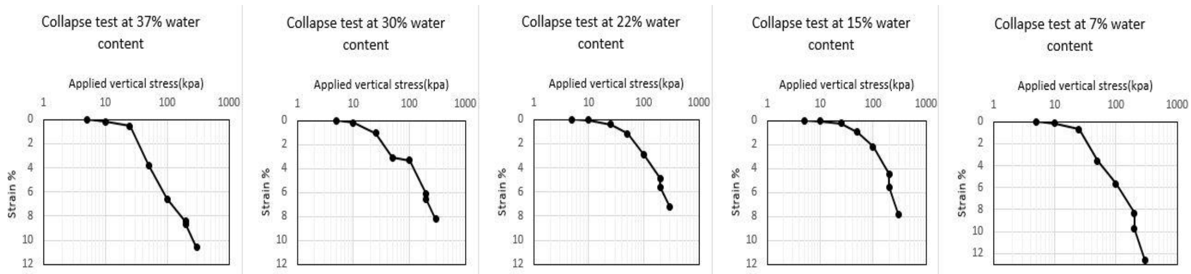

Figure.5.18 Collapse test Result at dry density of 0.63 gm/cm^3

Figure 5.16 to Figure 5.18 shows the test result between applied vertical stress (kPa) vs strain (%). At dry density 1.05 gm/cc and water content 37 % the collapse potential is 0.08% which is less than 1%. At dry density 0.84 gm/cc and water content 7% the collapse potential is more than one which shows that at this condition the pond ash is moderately collapse. At density 0.63 gm/cc and water content 15 and 7% the collapse potential is more than one as compare to the collapse potential at 100 kPa.

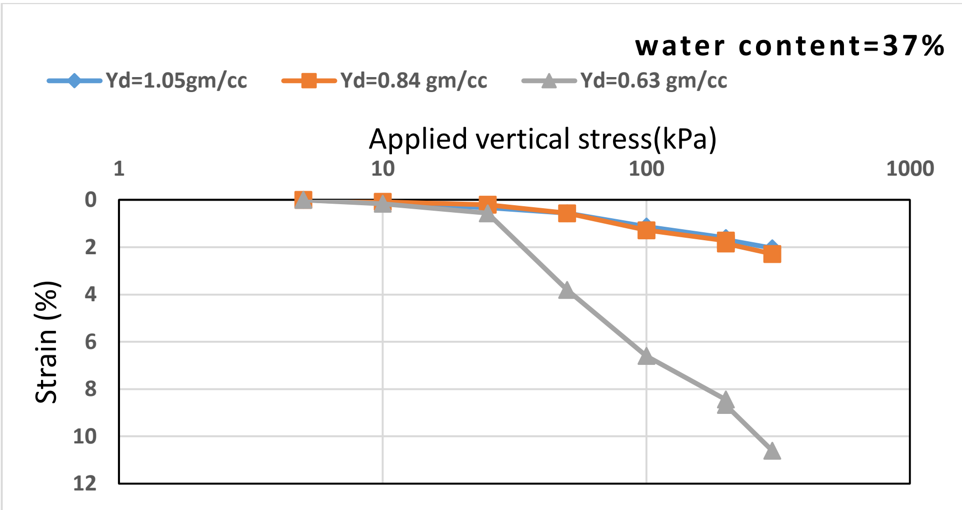

Figure.5.19 Collapse test Result at different dry density of water content 37%

Figures 5.19 to 5.23 the initial water content is respectively 37%, 30 %, 22%, 15% and 7%. In this case the potential collapse decreases while increasing applied dry density. The highest rate of collapse is obtained for a density of 0.63 gm/cc and a water content of 15% and 7%, the rate of collapse are 1.08 and 1.44%. This phenomenon is done by the mechanism that occurs after flooding at load of 200 kPa. In order to establish the influence of dry density and water content on collapse potential of the studied pond ash, shown in Table 5.2 and plotted the variation of collapse potential with both dry density (Figure 5.24) and the water content (Figure 5.25).

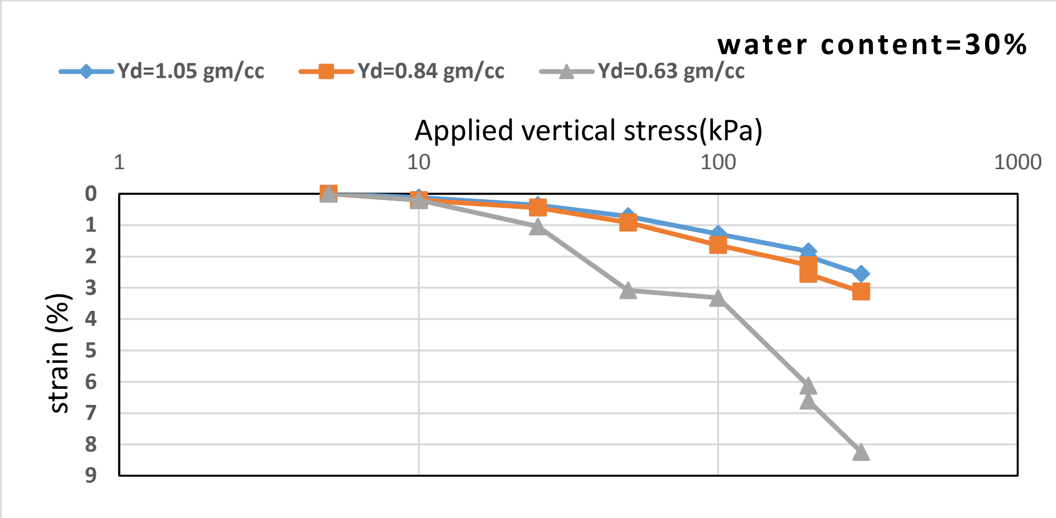

Figure.5.20 Collapse test Result at different dry density of water content 30%

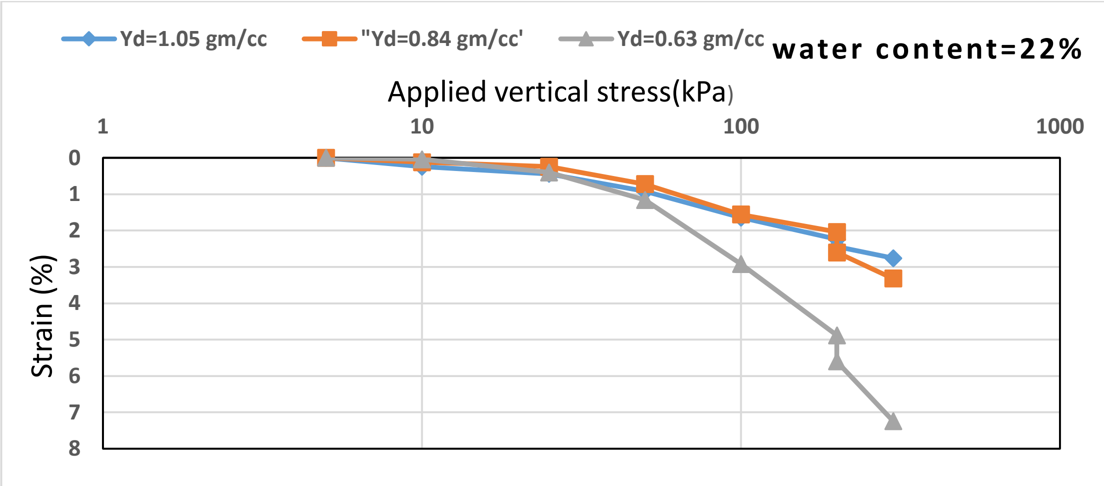

Figure.5.21 Collapse test Result at different dry density of water content 22%

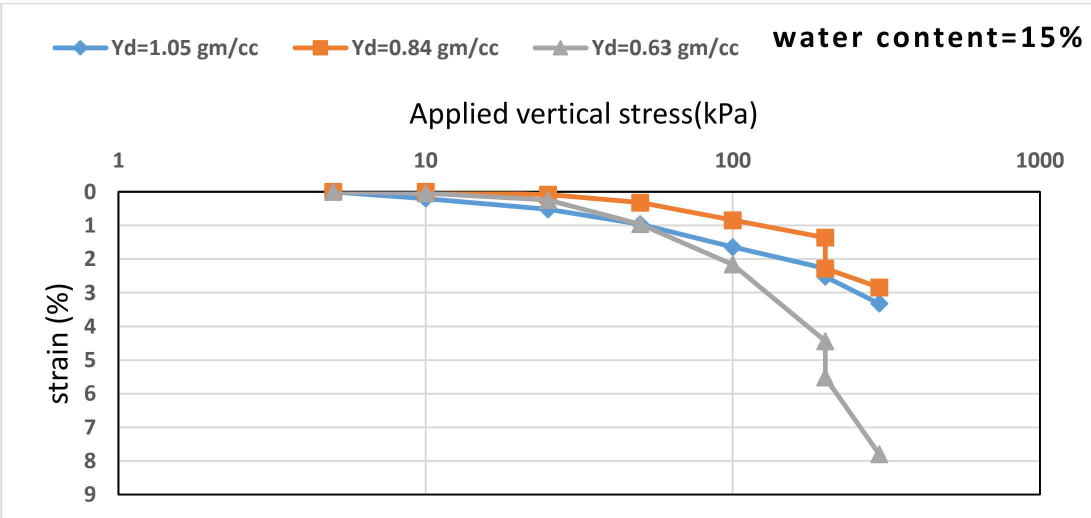

Figure.5.22 Collapse test Result at different dry density of water content 15%

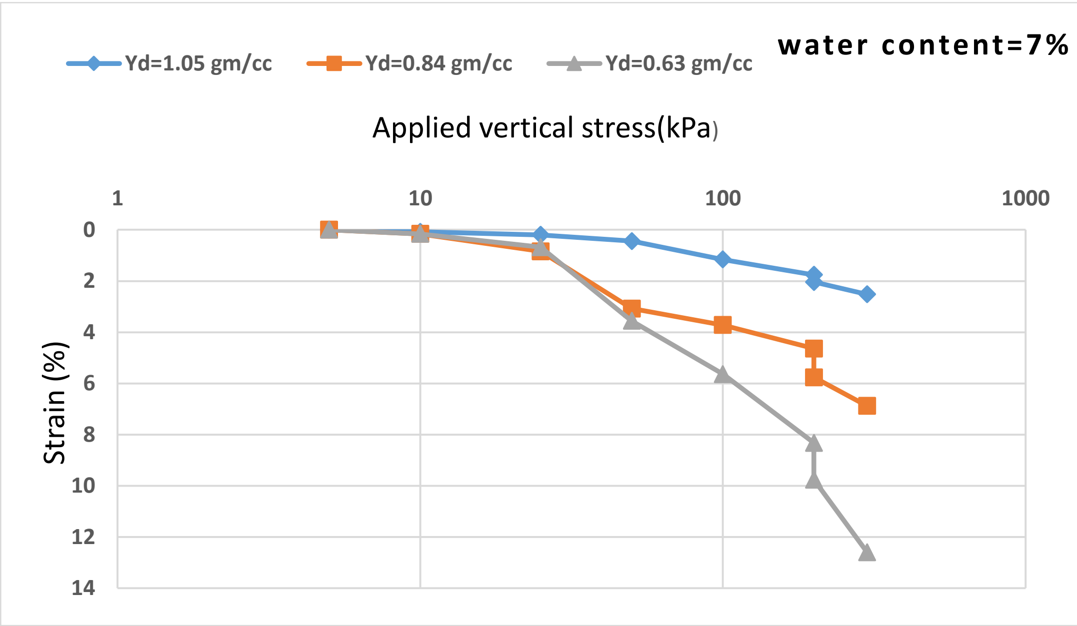

Figure.5.23 Collapse test Result at different dry density of water content 7%

Analysing the Table 5.2, the results are:

1. The lowest potential is obtained at the characteristics of standard Proctor optimum ($w=37\%, \Upsilon_d=1.05$ gm/cc)
2. At lower density and water content we found there is moderate potential of collapse (1.44%) for the Pond ash sample.

Table 5.2 Potential Collapse of Pond ash at 200 kPa

gm/cc ↓	W=37%	W=30%	W=22%	W=15%	W=7%
$\Upsilon_d=1.05$	0.08	0.16	0.20	0.21	0.24
$\Upsilon_d=0.84$	0.12	0.28	0.56	0.92	1.12
$\Upsilon_d=0.63$	0.32	0.48	0.72	1.08	1.44

Classification of Jennings and Knight (1975)
Legend:

	No Problem (CP from 0 to 1%)		Moderate Trouble (CP from 1 to 5%)
	Trouble (CP from 5 to 10%)		Severe Trouble (CP from 10 to 20%)
	Very Severe Trouble (CP > to 20%)		

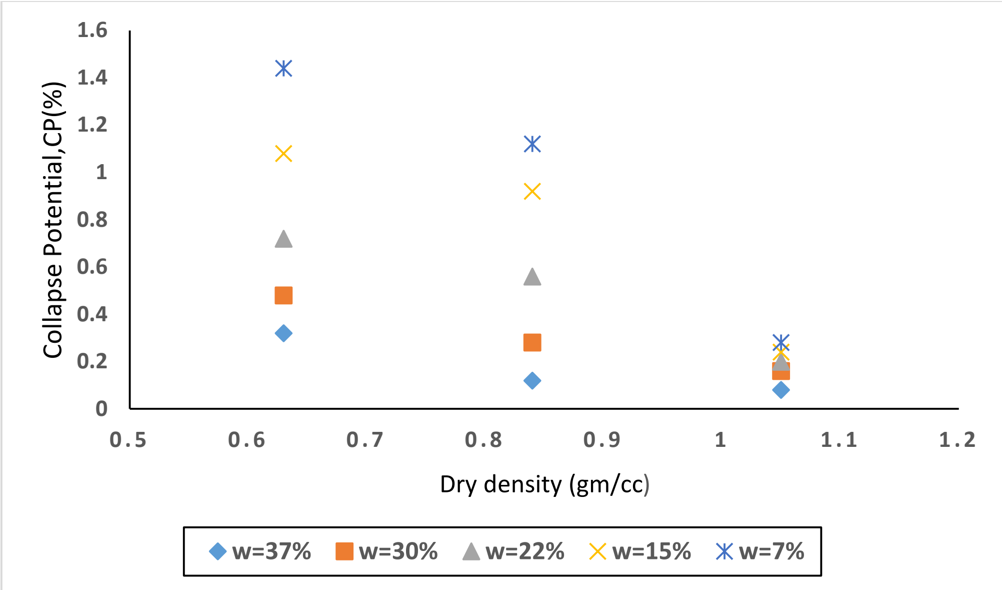

Figure 5.24 Effect of Collapse Potential at different Dry density

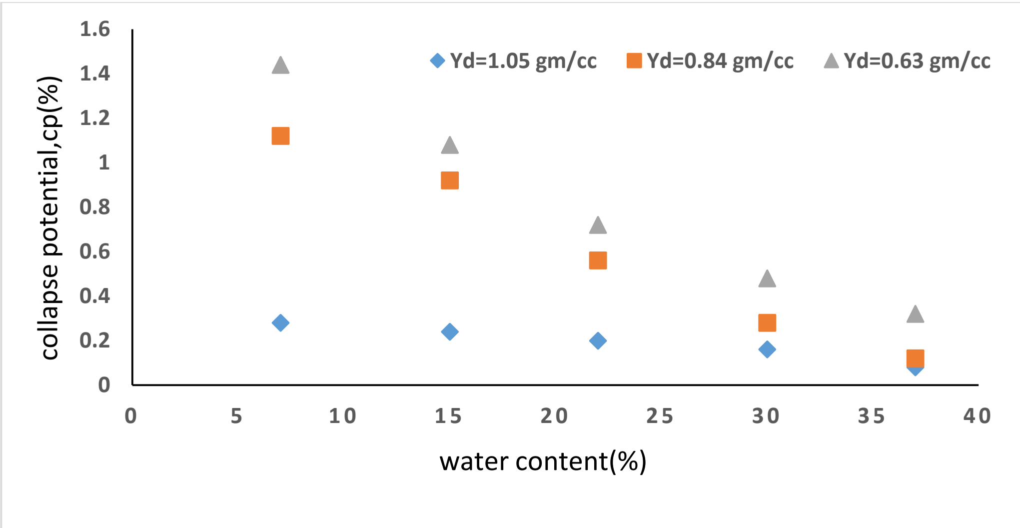

Figure 5.25 Effect of Collapse Potential at different Moisture content

The results in Table 5.2 are expressed as graphs (Figures 5.24 and 5.25). It clearly shows that there is an inverse relation between the collapse potential (CP) and dry density. The same thing is observed for the relation between CP and water content. At higher value of water content, we obtain a lowest potential of collapse. Also shows that the collapse potential increases with increase in vertical stress. A summary of the potential collapse of the Pond ash in 3D presentation is given in Figure 5.26.

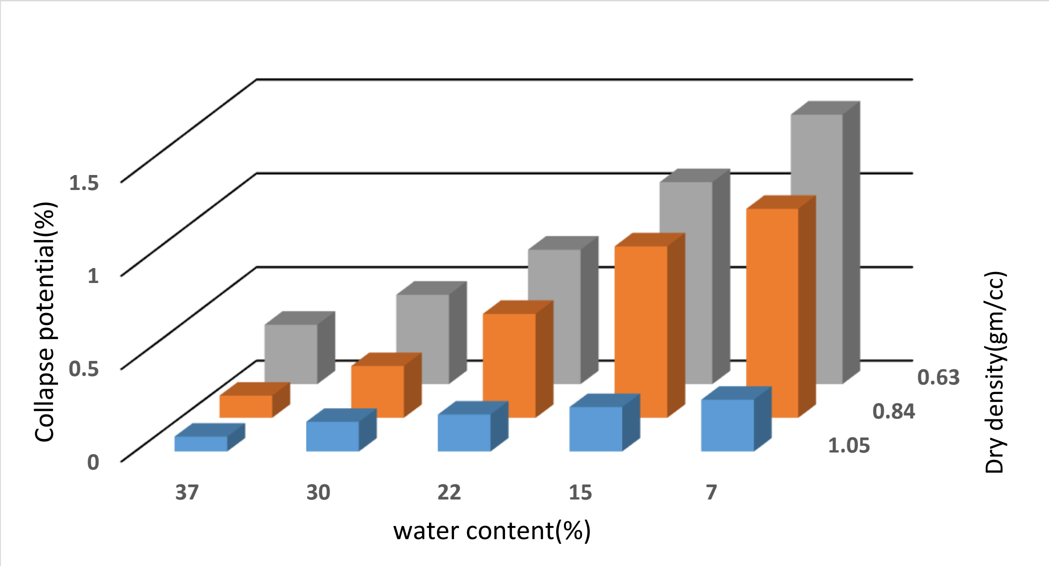

Figure 5.26 Summary of the potential collapse of Pond ash

(3D representation).

5.2.5.3 Collapse Test Result at different Dry Density and at different Moisture Content at a stress level of 300kPa

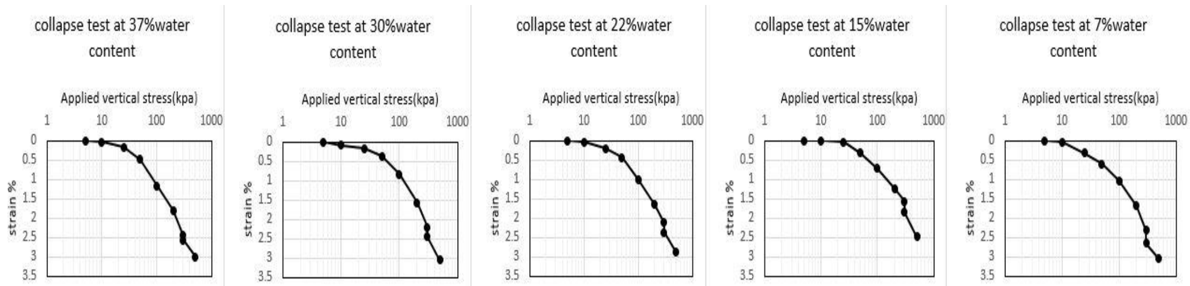

Figure 5.27 Collapse test Result at dry density of 1.05 gm/cm^3

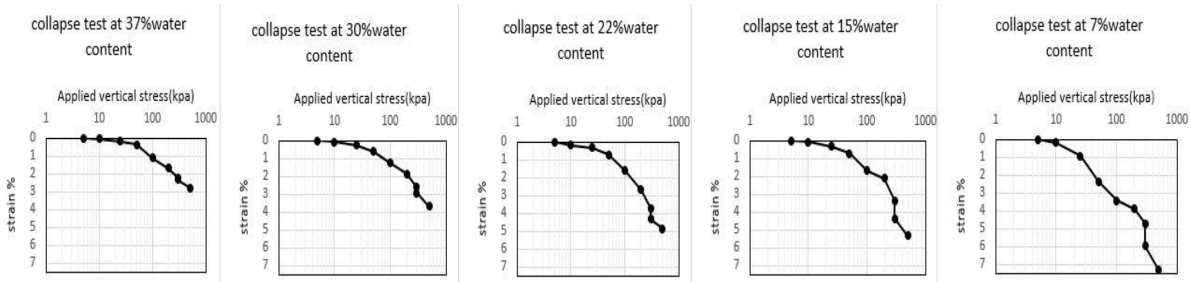

Figure 5.28 Collapse test Result at dry density of 0.84 gm/cm^3

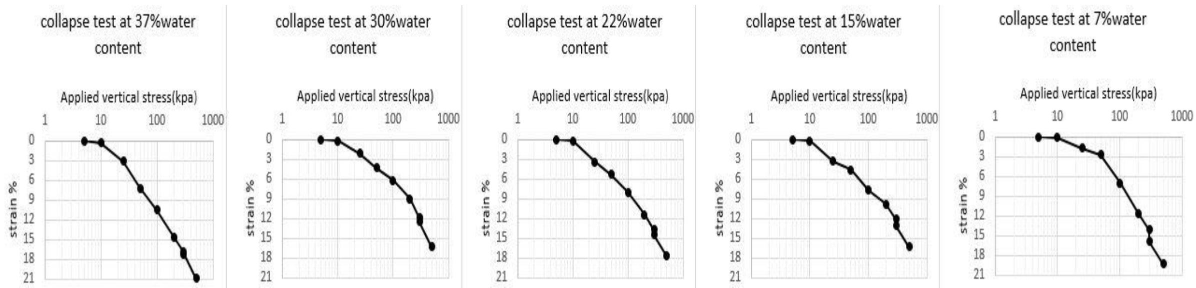

Figure 5.29 Collapse test Result at dry density of 0.63 gm/cm^3

At 300 kPa the collapse potential at dry density and water content respectively 1.05 gm/cc and 37%, is 0.12% (Figure 5.27).At same water content (37%), and decreasing the initial density of 1.05 gm/cc to 0.84 gm/cc and 0.63 gm/cc, higher potentials of collapse are obtained (Figure 5.30). Figures 5.31 to 5.34 the initial water content is respectively 30 %, 22%, 15% and 7%. In this case the potential collapse decreases while increasing applied dry density. The highest rate of collapse is obtained for a density of 0.63 gm/cc and a water content of 7%, the rate of collapse is 1.80%. This phenomenon is done by the mechanism that occurs after flooding at load of 300 kPa. In order to establish the influence of dry density and water content on collapse potential of the studied pond ash, which shown in (Table 5.3) and plotted the variation of collapse potential with both dry density (Figure 5.35) and the water content (Figure 5.36).

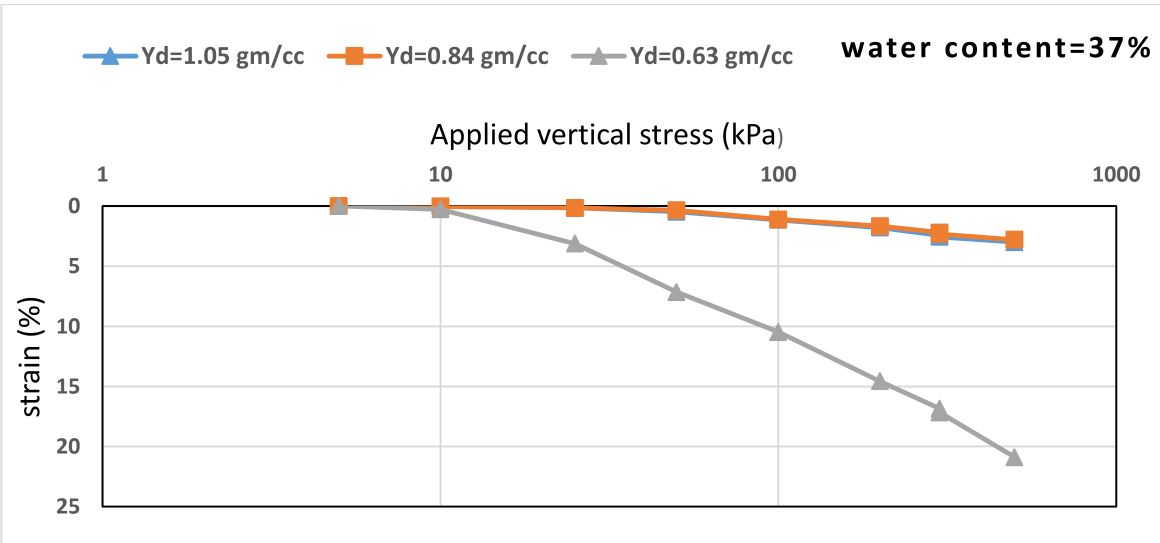

Figure 5.30 Collapse test Result at different dry density of water content 37%

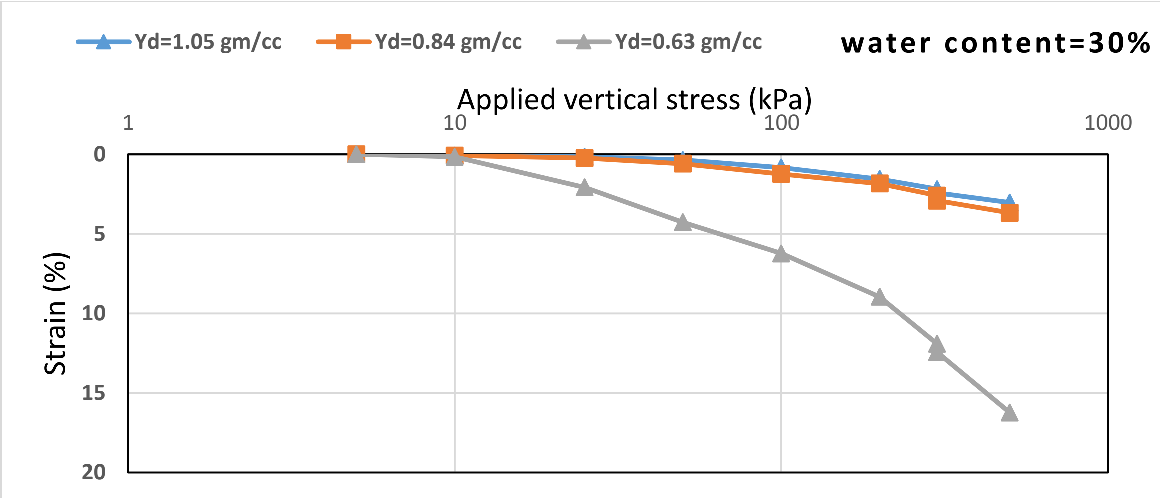

Figure 5.31 Collapse test Result at different dry density of water content 30%

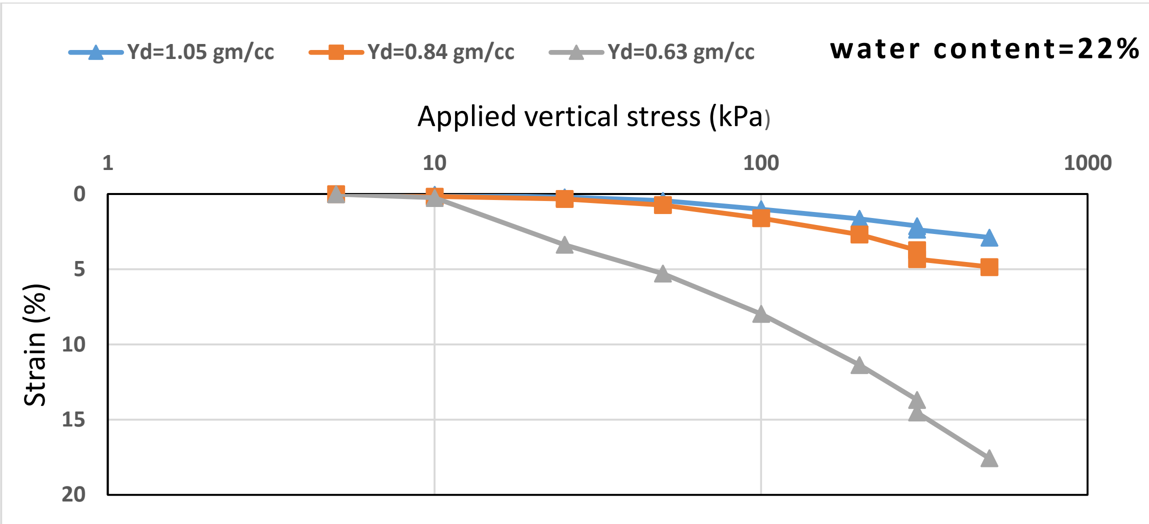

Figure 5.32 Collapse test Result at different dry density of water content 22%

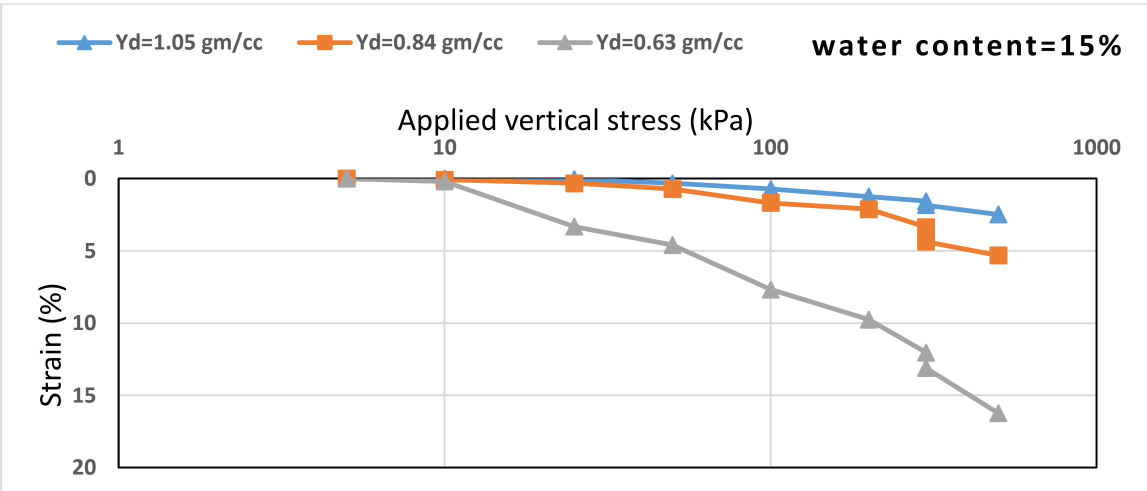

Figure 5.33 Collapse test Result at different dry density of water content 15%

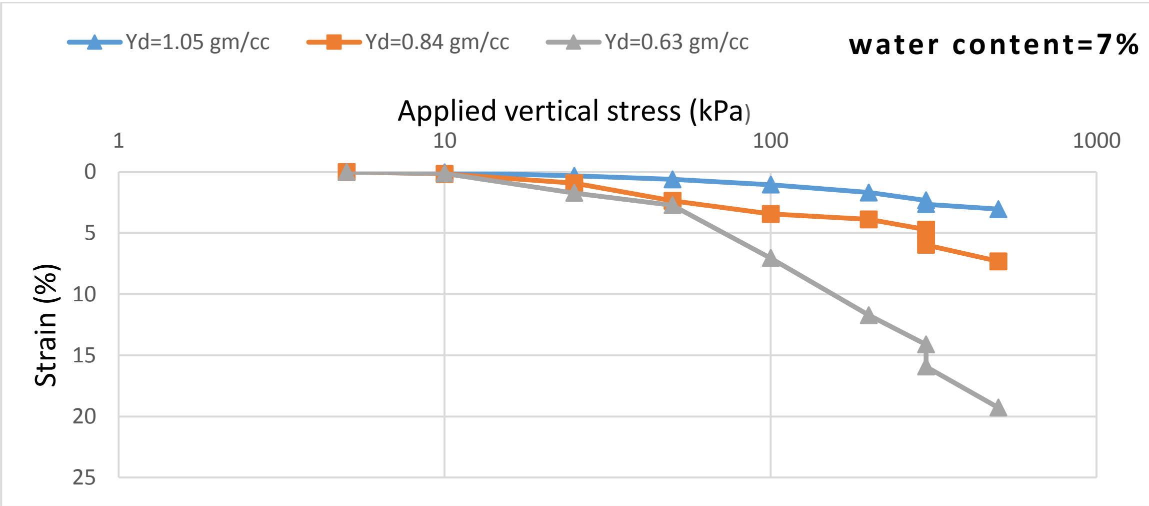

Figure 5.34 Collapse test Result at different dry density of water content 7%

Analysing the Table 5.3, the results are:

1. The lowest potential is obtained at the characteristics of standard Proctor optimum (w=37%,γ_d=1.05 gm/cc)
2. At lower density and water content, there is moderate potential of collapse (1.80%) obtained for the Pond ash sample.

Table 5.3 Potential Collapse of Pond ash at 300kPa

gm/cc	W=37%	W=30%	W=22%	W=15%	W=7%
γ_d=1.05	0.12	0.24	0.24	0.28	0.32
γ_d=0.84	0.12	0.32	0.60	1.00	1.24
γ_d=0.63	0.32	0.52	0.84	1.08	1.80

Classification of Jennings and Knight (1975)
Legend:

No Problem (CP from 0 to 1%)	Moderate Trouble (CP from 1 to 5%)
Trouble (CP from 5 to 10%)	Severe Trouble (CP from 10 to 20%)
Very Severe Trouble (CP > to 20%)	

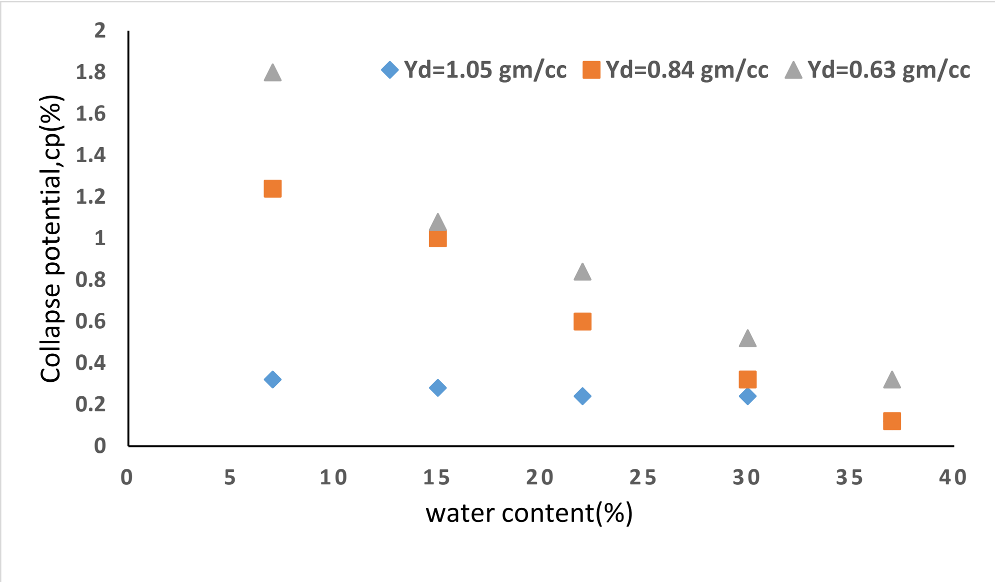

Figure 5.35 Effect of Collapse Potential at different Moisture content

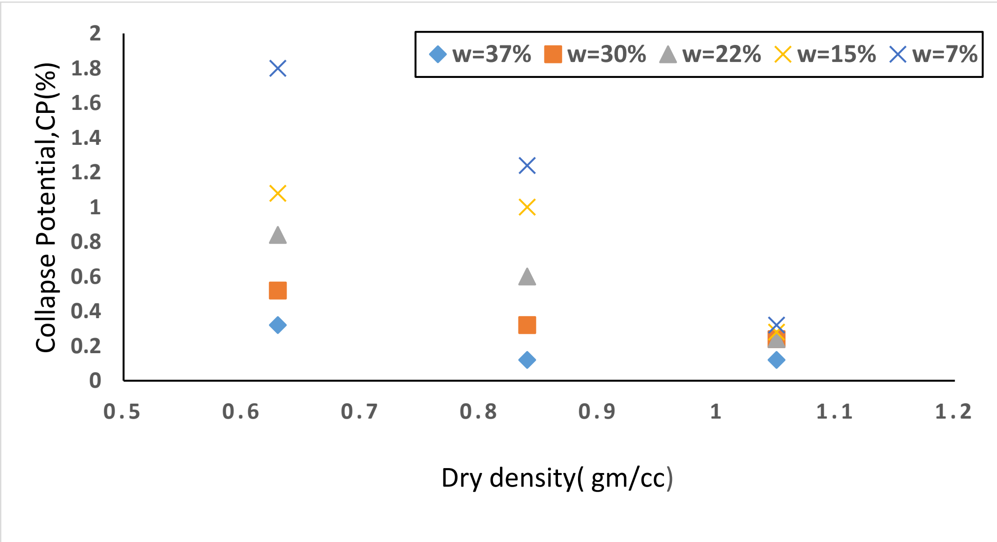

Figure 5.36 Effect of Collapse Potential at different Dry density

The results in Table 5.3 are expressed as graphs (Figures 5.35 and 5.36). The same thing is observed as in previous cases. At higher value of water content, we obtain a lowest potential of collapse. Also the collapse potential increases with increase in vertical stress. A summary of the potential collapse of the Pond ash in 3D presentation is given in Figure 5.37.

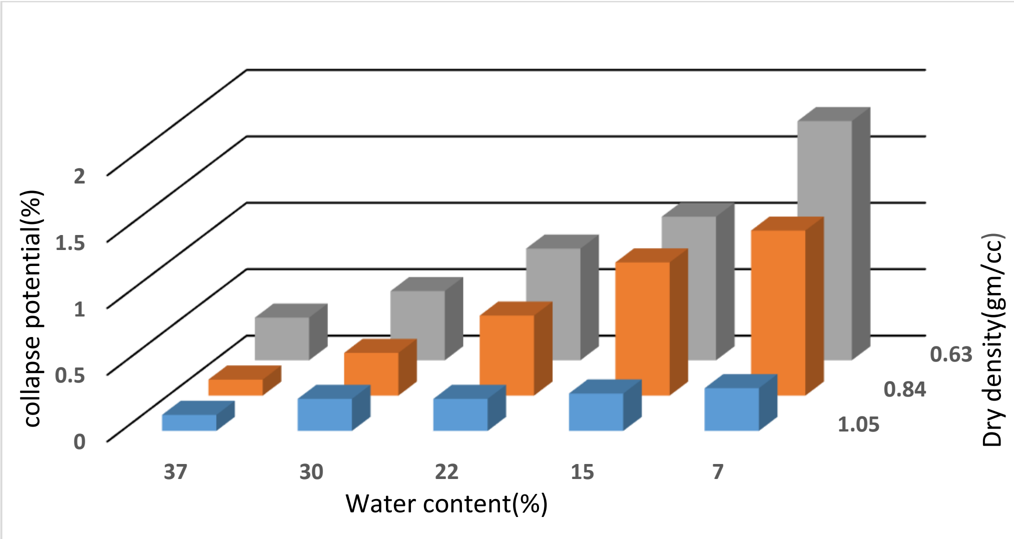

Figure 5.37 Variation of Collapse Potential at different Moisture content and dry density

From the above test results at different Vertical stress (100, 200 and 300 kPa) it concluded that the collapse potential increases with increase in Vertical stress. Figure 5.38 to 5.40 shows the relationship between collapse potential and vertical stress.

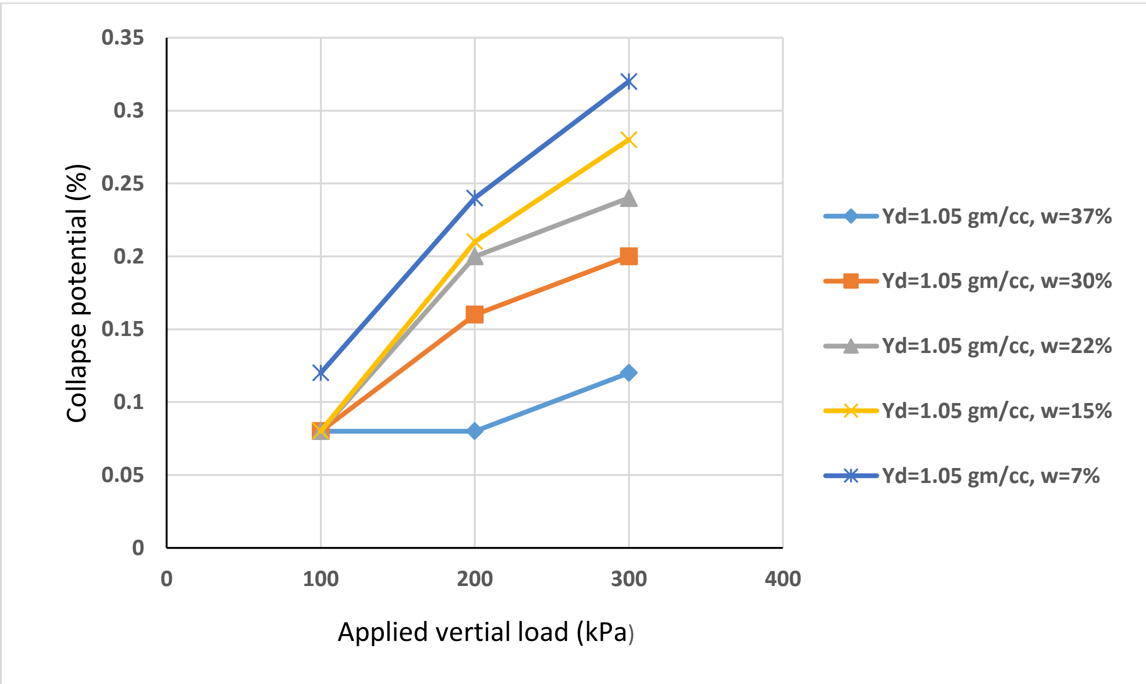

Figure 5.38 Variation of collapse potential with vertical stress at density 1.05 gm/cc

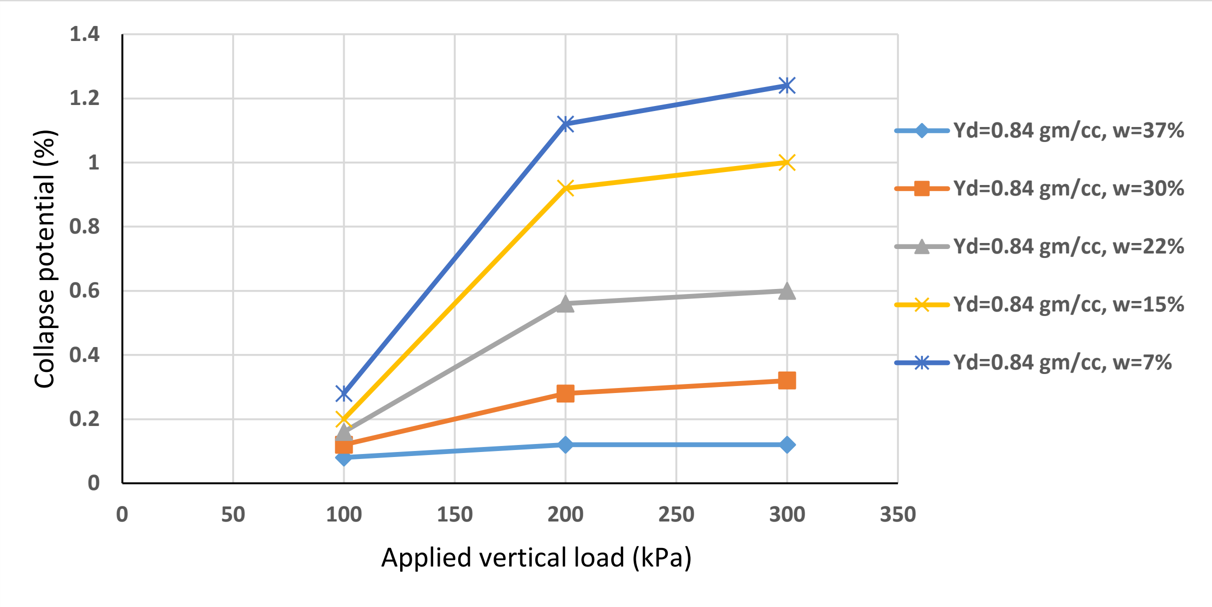

Figure 5.39 Variation of collapse potential with vertical stress at density 0.84 gm/cc

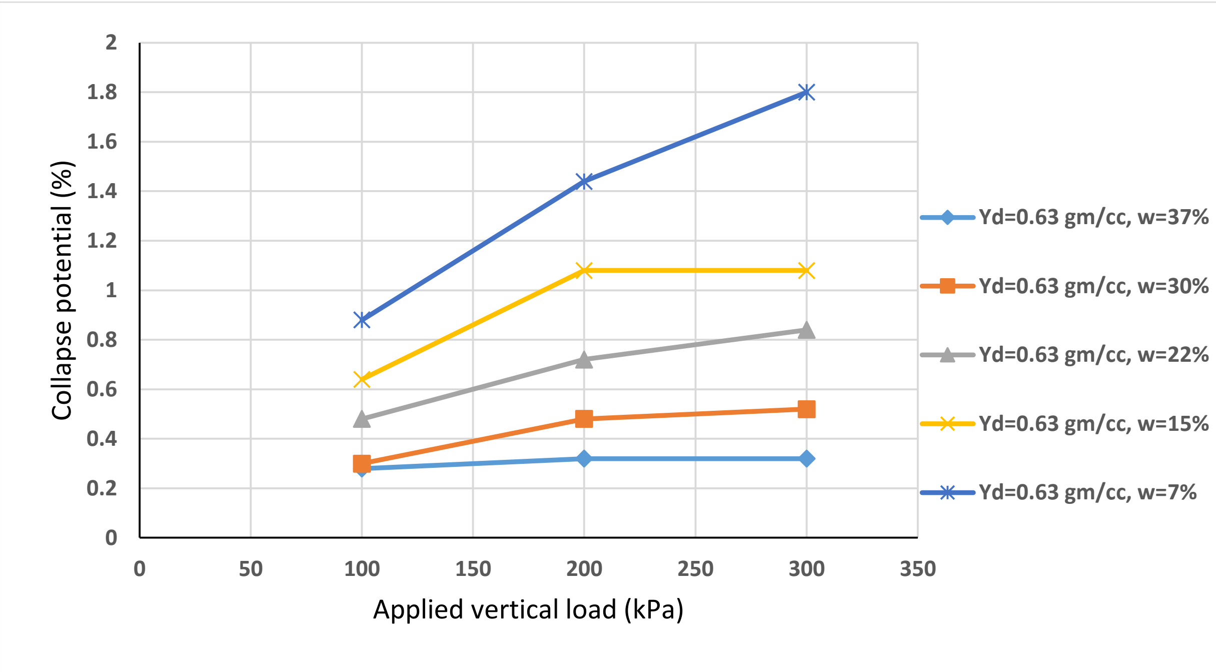

Figure 5.40 Variation of collapse potential with vertical stress at density 0.63 gm/cc

From Table 4.6 and Figure 5.3 it concluded that with increase in compaction energy (99734.32 to 520690.76 kg-m/m^3) the water content decreases (38.49 to 30.23%) and dry density increases (1.056 to 1.174 gm/cc). Figure 5.41 shows that at different compaction energy the collapse potential decreases with increase in compaction energy.

Table 5.4 Potential collapse at different compaction energy

Compaction Energy (kg-m/m^3)	OMC (%)	MDD (gm/cc)	CP (%)
99734.32	38.49	1.056	0.08
119681.18	36.03	1.070	0.06
347127.17	33.92	1.115	0.04
433908.96	30.51	1.165	0.02
520690.76	30.23	1.174	0.008

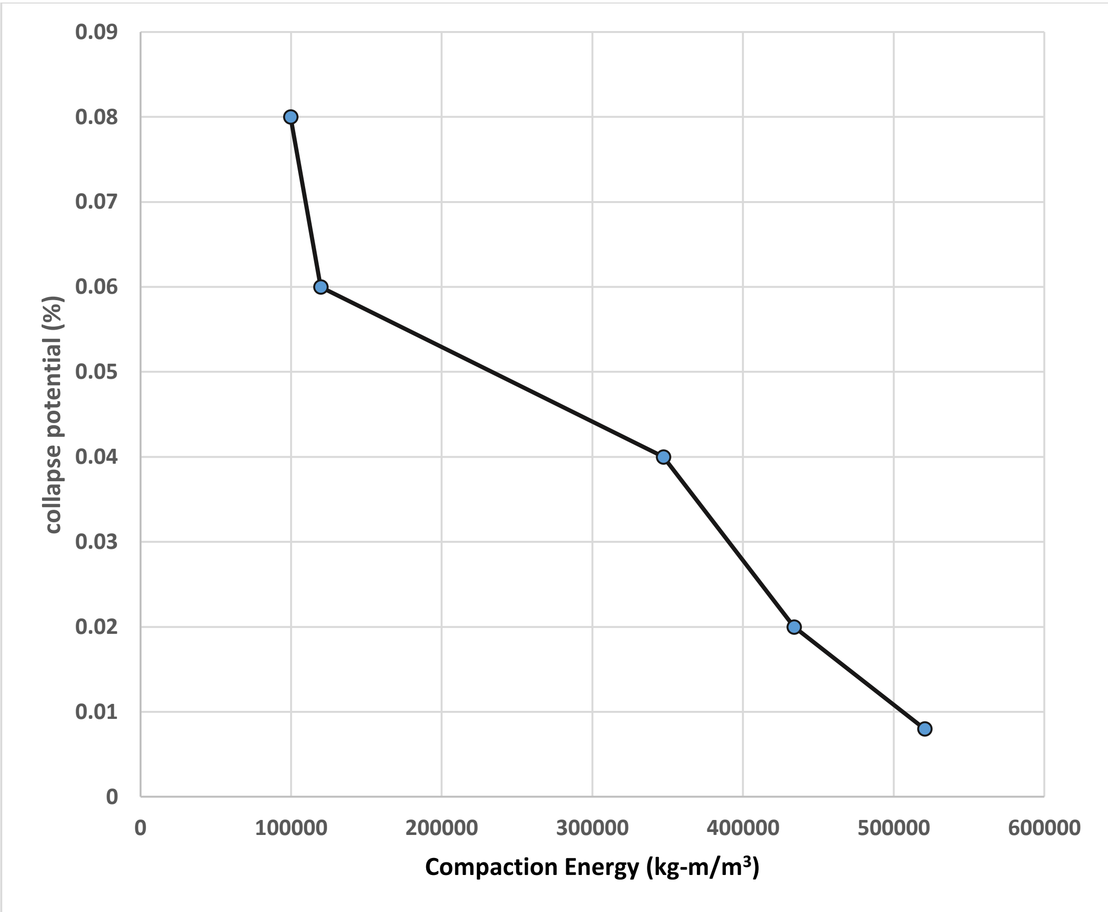

Figure 5.41 Effect of Collapse Potential at different Compaction Energy

6.1 Conclusion

The collapsibility of coal ash is one of the most important parameters for using ash as a fill material. The present work provides a framework for the assessment of collapsibility of the ashes. Several single oedometer collapse tests have been performed to test the collapsibility of coal ashes. Based upon the test results various outcomes of this study are summarized as:

- The collapse potential obtained by the oedometer test is a dependent parameter of several factors such as, stress level, degree of compaction, dry density, moisture content, etc.
- The collapse test carried out on Pond ash, it shows that the collapse potential at MDD and OMC is 0.08%.which indicates that it is non collapsible.
- It is observed that for constant water content, the potential of collapse increases when the dry density decreases. Also for constant dry density, the collapse potential increases with decrease in water content.
- The collapse potential increases with respect to increases in applied vertical stress.
- It is observed that with the increase in compaction energy the collapse potential decreases.
- For this reasons, the pond ash is compacted near the optimum to minimize the risks to obtain collapse phenomena.

6.2 Scope for Future Work

For effective functioning of pond ash, some more aspects have to be investigated

- Further researches can be done by conducting Double oedometer test, Field collapse test, and Model plate load collapse test to determine the collapse potential.

REFERENCES

1. Ayadat, T., & Hanna, A. (2007). Prediction of collapse behaviour in soil. *Revue européenne de génie civil*, *11*(5), pp 603-619.
2. Barden, L., McGown, A., & Collins, K. (1973). The collapse mechanism in partly saturated soil. *Engineering Geology*, *7*(1), pp 49-60.
3. Barden, L., Madedor, A. O., & Sides, G. R. (1969). Volume change characteristics of unsaturated clay. *Journal of Soil Mechanics & Foundations Div*.
4. Basma, A. A., & Tuncer, E. R. (1992). Evaluation and control of collapsible soils. *Journal of Geotechnical Engineering*, *118*(10), pp 1491-1504.
5. Benchouk, A., Abou-Bekr, N., & Taibi, S. (2013). Potential collapse for a clay soil. *International Journal of Emerging Technology and Advanced Engineering*, *3,* pp 43-47.
6. Booth, A. R. (1977). Collapse settlement in compacted soils. *Council for Scientific and Industrial Research,* Research Report 324, National Institute for Transport and Road Research Bulletin 13, pp. 1-34.
7. Booth, A. R. (1975, September). The factors influencing collapse settlement in compacted soils. *In Proc. 6th Reg. Conf. for Africa on SMFE,* Durban (Vol. 1, pp. 57-63).
8. Cox, D. W. (1979). Volume change of compacted clay fill. In *Proceedings from the Clay Fills Conference, held at the Institution of Civil Engineers, November pp-14-15, 1978.*
9. Darwell, J. L., Denness, B., & Conway, B. W. (1976). Prediction of metastable soil collapse. *Proceedings of the Anaheim*.
10. Dudley, J. H. (1900). Review of collapsing soils. *Journal of Soil Mechanics & Foundations Div*, *97*(SM1).
11. El Sohby, M. A., & Rabbaa, S. A. (1984). Deformational behaviour of unsaturated soils upon wetting. In *Regional conference for Africa. 8* (pp. 129-137).
12. El-Sohby, M. A., & Elleboudy, A. M. (1987). Swelling and collapsible behaviour of unsaturated cemented sand upon wetting. In *European conference on soil mechanics and foundation engineering. 9* (pp. 553-556).

13. Ghosh, P., & Goel, S. (2014). Physical and Chemical Characterization of Pond Ash. *International Journal of Environmental Research and Development. ISSN*, pp 2249-3131.
14. Houston, S. L., Houston, W. N., & Spadola, D. J. (1988). Prediction of field collapse of soils due to wetting. *Journal of Geotechnical Engineering*, *114*(1), pp 40-58.
15. Huang, D. (1989). *A laboratory investigation on the behaviour of collapsible soil*.
16. Jakka, R. S., Ramana, G. V., & Datta, M. (2010). Shear behaviour of loose and compacted pond ash. *Geotechnical and Geological Engineering*, *28*(6), pp 763-778.
17. Jennings, J. E., & Knight, K. (1975). *A guide to construction on or with materials exhibiting additional settlement due to" collapse" of grain structure* 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, pp. 99–105.
18. Jotisankasa, A., Ridley, A., & Coop, M. (2007). Collapse behaviour of compacted silty clay in suction-monitored oedometer apparatus. *Journal of Geotechnical and Geoenvironmental Engineering*, *133*(7), pp 867-877.
19. Kaniraj, S. R., & Gayathri, V. (2004). Permeability and consolidation characteristics of compacted fly ash. *Journal of energy engineering*, *130*(1), pp 18-43.
20. Kumar Bera, A., Ghosh, A., & Ghosh, A. (2007). Compaction characteristics of pond ash. *Journal of materials in civil engineering*, *19*(4), pp 349-357.
21. Lawton, E. C., Fragaszy, R. J., & Hardcastle, J. H. (1991). Stress ratio effects on collapse of compacted clayey sand. *Journal of Geotechnical Engineering*, *117*(5), 714-730.
22. Lawton, E. C., Fragaszy, R. J., & Hardcastle, J. H. (1989). Collapse of compacted clayey sand. *Journal of Geotechnical Engineering*, *115*(9), 1252-1267.
23. Lawton, E. C., Fragaszy, R. J., & Hetherington, M. D. (1992). Review of wetting-induced collapse in compacted soil. *Journal of geotechnical engineering*, *118*(9), 1376-1394.
24. Lutenegger, A. J., and Saber, R. T. (1988). ‘‘Determination of collapse potential of soils.’’ *GTJ*, 11(3), 173–178.
25. Moore, P. J., & Millar, D. V. (1900). “The collapse of sand upon saturation”. In *Proc Aust-nZ Conf Geomech/Australia/* (Vol. 1).
26. Naik, H., & Maqbool, S., Butt, W. A., Gupta, K (2015). “Collapsible behaviour of compacted coal ash”. *International Journal*, *3*(1), 272-275.

27. Pereira, J. H., & Fredlund, D. G. (2000). Volume change behaviour of collapsible compacted gneiss soil. *Journal of Geotechnical and Geoenvironmental Engineering*, *126*(10), 907-916.
28. Popescu, M. E. (1986). A comparison between the behaviour of swelling and of collapsing soils. *Engineering Geology*, *23*(2), 145-163.
29. Raymon, S. (1961). Pulverized fuel ash as embankment material. *Proceedings of the Institution of Civil Engineers*, *19*(4), 515-536.
30. Sasitharan, S., Robertson, P. K., Sego, D., & Morgenstern, N. R. (1993). Collapse behaviour of sand. *Canadian Geotechnical Journal*, *30*(4), 569-577.
31. Sekhar Madhyannapu, R., Madhav, M. R., Puppala, A. J., & Ghosh, A. (2008). Compressibility and collapsibility characteristics of sedimented fly ash beds. *Journal of Materials in Civil Engineering, 20*(6), 401-409.
32. Skarzynska, K. M., Rainbow, A. K. M., & Zawisza, E. (1989). Characteristics of ash in storage ponds. In *Proc. Twelfth Int. Conf. on SM & FE* (pp. 1915-1918).
33. Sridharan, A., Pandian, N. S., & Srinivas, S. (2001). Compaction behaviour of Indian coal ashes. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, *5*(1), 13-22.
34. Tadepalli, R., & Fredlund, D. G. (1991). The collapse behaviour of a compacted soil during inundation. *Canadian geotechnical journal*, *28*(4), 477-488.
35. Trivedi, A., & Sud, V. K. (2004). Collapse behaviour of coal ash. *Journal of geotechnical and geoenvironmental engineering*, *130*(4), 403-415.
36. Trivedi, A., & Sud, V. K. (2002). Grain characteristics and engineering properties of coal ash. *Granular Matter, 4*(3), 93-101.
37. Trivedi, A., Pathak, R., & Gupta, R. (2009). A common collapse test for granular materials. In *Indian Geotechnical Conference* (pp. 47-51).

.

.

.